ABOVE AND BELOWGROUND DRIVERS OF WEED-SOYBEAN COMPETITION IN A LONG-TERM ORGANIC CROPPING SYSTEMS EXPERIMENT

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ABSTRACT

Increased weed free production capacity and decreased weed-crop competition intensity could help explain apparent crop tolerance of weeds in organic systems. The weed community and soil environment are affected by management history and could influence weed-crop competition relationships. We investigated weed-soybean competition in four organic cropping systems: (i) High Fertility (HF), (ii) Low Fertility (LF), (iii) Enhanced Weed Management (EWM), and (iv) Reduced Tillage (RT). In our experiment, the RT system had greater weed-free soybean production capacity, greater soil health, but also greater weed abundance and diversity than the EWM system. Soil inorganic N, K, Ca, and respiration were positively related to weed-free soybean production capacity. Unexpectedly, we observed positive relationships between weed-soybean competition intensity and several soil nutrient and organic matter indicators. Our research highlights connections between management history and weed-crop competition in organic systems, which could inform integrated weed management strategies.

BIOGRAPHICAL SKETCH

Margaret Ball grew up in Watkins Glen, NY and earned a B.A. in Anthropology from the University of Rochester. She is employed as Agriculture Development Specialist at Cornell Cooperative Extension of Tioga County. She and Jake DeLisle operate a small farm business, Roaming Root, in Willseyville, NY.

Dedicated to Jake

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
EWM	Enhanced Weed Management
fPOM	Free particulate organic matter
LF	Low Fertility
HF	High Fertility
OCS	Organic Cropping Systems Experiment
OM-LOI	Organic matter (loss on ignition)
oPOM	Occluded particulate organic matter
PLSR	Partial Least Squares Regression
RPDH	Resource Pool Diversity Hypothesis
RT	Reduced Tillage
SM	Standard Management
SS	Supplemented Seedbank
WB	Weed biomass
WD	Weed density
WF	Weed Free

ABOVE AND BELOWGROUND DRIVERS OF

WEED-SOYBEAN COMPETITION

IN A LONG-TERM ORGANIC

CROPPING SYSTEMS EXPERIMENT

PROLOGUE

Terms

All plants need the same basic resources (space, water, light, and food). When plants growing near one another use up scarce resources, thus limiting the supply of resources for their neighbors, the plants are said to *compete*. When *weeds* (unwanted plants) compete with *crops* (wanted plants), this is called *weed-crop competition*.

Measures of crop production in agronomic research include *crop biomass* (the weight of crop plant matter in a defined area) and *crop yield* (the quantity of harvestable product in a defined area). Measures of weed abundance include *weed density* (the number of weeds in a defined area) and *weed biomass* (the weight of weeds in a defined area). Cropping systems are understood to have theoretical "properties" that can be observed through tangible measures. Two cropping system properties often discussed in weed-crop competition research are *weed-free production capacity* (crop production in the absence of weeds) and *weed-crop competition intensity* (the degree to which a given weed abundance reduces crop production).

Motives

Farmers face many challenges, and weeds are common to all[1]. Weeds are a major agricultural pests, causing at least $15 billion in economic damage in the United States annually (Bridges 1994). Widely used chemical and mechanical weed control practices are linked with problems including herbicide resistance (Heap 2016) and decreased soil health (Moebius-Clune et al. 2016). It is recognized that new, integrated strategies for weed control must be developed (Bàrberi 2002, Buhler 2002, Gallandt 2014, Liebman and Gallandt 1997, Mortensen et al. 2000).

[1] with the possible exception of Mark Watney (*The Martian*).

Managing weed-crop competition is an important aspect of weed management (Bastiaans et al. 2008). Many components of cropping systems (e.g., crop rotation, cover crops, seeding rates, nutrient inputs) influence weed-crop competition and are important to consider in developing potential management strategies (Bàrberi 2002, Buhler 2002, Gallandt 2014, Liebman and Gallandt 1997, Mortensen et al. 2000). Weed species, soil nutrient status, and other soil factors could all affect competition intensity between weeds and crops. Studying these factors in a whole-systems context is important to inform the development of new approaches to integrated weed management.

Organic crops usually encounter more weeds than conventional crops, because the mechanical and cultural weed control methods permitted under organic production tend to be less effective than non-organic chemical control methods. Weed management is a major research priority cited by organic farmers (Baker and Mohler 2014). Organic systems often, but not always, yield similarly to conventional systems despite greater weed abundance, suggesting an improved crop tolerance of weeds under organic management (Davis et al. 2005, Delate and Cambardella 2004, Hiltbrunner et al. 2008, Ryan et al. 2009, 2010a). Experiments at the Rodale Institute reported that corn under long-term organic management could tolerate greater weed abundance than corn under conventional management without suffering a yield reduction (Ryan et al. 2009, 2010a). Increased yield capacity and reduced weed-crop competition intensity were two possible explanations contributing to the apparent crop tolerance of weeds (Ryan et al. 2010a).

Cropping system management history could affect weed-crop competition through above and belowground mechanisms. Management practices including crop rotation, tillage, nutrient inputs, and weed management practices can cause weed community composition to shift over time (Menalled et al. 2001, Ryan et al. 2010b). The species of weeds and crops under consideration have a major influence on weed-crop competition dynamics (Swanton et al. 2015, Zimdahl 2004), so it is possible that weed community differences between organic and conventional systems could contribute to reduced weed-crop competition intensity. Long-term organic management of cropping systems is known to influence soil properties including organic matter (Marriott and Wander 2006) and soil nitrogen (N) mineralization (Spargo et al. 2011). These soil properties are likely to affect weed-free production capacity and weed-crop competition intensity within a cropping system, but their particular effects and potential interactions between them are still poorly understood (Smith et al. 2010).

Weed-crop relationships have been studied in organic corn, but not often in organic grain legume crops such as soybean. The ability of soybean to fix atmospheric N through a symbiotic relationship with rhizobia changes its nutrient uptake patterns compared with a non-N-fixing crop with large N demand such as corn. Increased soil inorganic N and occluded particulate organic matter N have been associated with decreased soybean N fixation rates (Schipanski et al. 2010). Variability of N fixation in response to both available soil N and N uptake of co-occurring weeds might influence the relationships between the soil environment, weed-free production capacity, and weed-crop competition intensity in soybean and other grain legume crops.

Previous research compared weed-crop relationships between organic and conventional cropping systems, but to our knowledge no studies have explicitly compared weed-crop relationships among organic systems with differing management histories. Because specific management practices could alter weed-crop relationships among different organic systems, understanding the effects of management history on weed-crop competition relationships is important in developing strategies that promote crop tolerance of weeds.

Experiment

This thesis describes the influence of management history on weed-soybean competition in the Cornell Long-Term Organic Cropping Systems Experiment (OCS). The OCS compared four organic grain cropping systems that varied in nutrient inputs, weed management, and tillage practices (Caldwell et al. 2014). We measured a suite of response variables (soybean and weed growth, weed communities, and soil properties) in the four cropping systems over two growing seasons, and manipulated weed abundance in nested plots to observe soybean response. We asked how specific long-term management practices (i.e. nutrient inputs, tillage intensity) might affect weed-crop competitive interactions through above and belowground drivers.

Each chapter of the thesis focuses on a possible driver of weed-soybean competition. Chapter 1 addresses aboveground drivers, focusing on weed community structure (abundance and species composition). Chapter 2 addresses belowground drivers, focusing on soil the soil environment.

CHAPTER 1

ABOVEGROUND DRIVERS OF COMPETITION: WEED COMMUNITY

Abstract

Weed management is a major challenge in organic crop production, and organic farms have been shown to harbor larger weed populations and more diverse communities than conventional farms. Because weed species vary in their competitive relationships with crops, and weed communities can be affected by management practices, intentionally selecting for a less competitive weed community that supports greater crop yields could be a cultural weed management strategy to complement other objectives such as maximizing ecosystem services. However, little research has been conducted on the effects of different organic management practices on weed communities and their effect on crop yields. In 2014 and 2015, weed abundance, community structure, and soybean performance were measured in a long-term experiment that compared four organic cropping systems: (i) High Fertility (HF), (ii) Low Fertility (LF), (iii) Enhanced Weed Management (EWM), and (iv) Reduced Tillage (RT). We used a split-plot randomized complete block design with cropping system as main plots and two weed treatment sub-plots: Weed Free and Standard Management. Weed communities were more diverse, weed densities were greater, and soybean yield was greater in the RT system compared to the EWM system. Perennial weeds were present in all systems, but species composition differed between RT and other systems. However, weed community differences between systems did not measurably affect crop performance or weed-crop competition. Our results show that relatively small differences in management practices can have a large impact on weed abundance, community composition, and soybean performance, and we suggest that a greater understanding of these effects could be used to improve weed management in organic cropping systems.

Introduction

Weed management can be challenging in organic grain crop production because of reliance on mechanical weed control practices such as cultivation, which can vary in efficacy based on soil and weather conditions. In addition to mechanical weed control, organic farmers often use cultural weed management practices that help regulate weed populations and reduce the negative impact of weeds on crop production (Bastiaans et al. 2008).

Weed abundance and community composition can be affected by cropping system management practices including crop rotation, tillage type and timing, nutrient input levels, and weed management practices (Davis et al. 2005, Hiltbrunner et al. 2008, Menalled et al. 2001, Ryan et al. 2010b). For example, Gruber and Claupein (2009) reported that weed density and weed seedbank density were greater in organic plots managed with chisel plow tillage compared to moldboard plow tillage. Reducing tillage can also facilitate a shift in weed communities toward perennial weeds (Thomas et al. 2004). The form in which nutrients are supplied can affect weed growth (Davis and Liebman 2001) and weed community composition (Menalled et al. 2001) depending on the nutrient responsiveness of particular weed species.

Since different species of weeds compete differently with crops (Swanton et al. 2015, Zimdahl 2004), differences in weed community might change the competitive relationship between weeds and crops. For example, in a recent greenhouse experiment in Maryland, researchers found that competitive relationships with corn differed among the two weeds used in the experiment (*Setaria faberi* Herrm. and *Amaranthus hybridus* L.) (Poffenbarger et al. 2015). The researchers suggested that weed community might influence the degree of crop-weed N resource partitioning in field conditions (Poffenbarger et al. 2015).

Weeds are more abundant and diverse in organic cropping systems compared to conventional cropping systems where synthetic herbicides are used (Hiltbrunner et al. 2008, Menalled et al. 2001, Ryan et al. 2010b). Previous research has reported a negative relationship between weed species diversity and crop yield (Davis et al. 2005). However, little is known about how different organic management strategies might affect weed communities. Understanding the factors that influence weed abundance and community composition could aid in the development of improved management practices that reduce the negative impact of weeds on crop performance. Shifting weed communities toward species that are weakly competitive against crops could be an important addition to integrated weed management strategies.

We conducted a nested experiment within the Cornell Organic Grain Cropping Systems Experiment (OCS) in central New York State to evaluate the impact of different organic grain management practices on weed community structure and soybean performance.

Materials and Methods

Long-term Experiment. The OCS experiment was initiated in 2005 at the Cornell University Musgrave Research Farm in Aurora, NY, USA, (42.73’ N, 76.66’ W). The soil was a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs) with partial tile drainage and pH near 7.8. A split-plot randomized complete block design with four replications was used to compare four organic cropping systems (main plots) that varied in nutrient inputs, weed management, and tillage practices. Two crop rotation entry points (split plots) were used so that two crops were represented in each system each year. Split plots measured 9.1 m x 30.5 m (12.2 m x 36.6 m including borders).

Cropping Systems. The four cropping systems maintained distinct guiding principles throughout the duration of the long-term experiment (2005-2015), though management practices varied slightly over time. The High Fertility (HF) system received multiple nutrient inputs including legume, composted chicken manure, and commercial organic fertilizers. The Low Fertility (LF) system received almost no nutrient input besides a legume cover crop. The Enhanced Weed Management (EWM) system received supplemental weed management, mainly additional tillage and cultivation. The Reduced Tillage (RT) system received less frequent and less intense tillage operations than other systems. The entire field site was managed using organic practices and was certified by the Northeast Organic Farming Association of New York (NOFA-NY). For a detailed description of management practices used from 2005-2010, see Caldwell et al. (2014).

Several changes were made to OCS management practices in 2011 to address emerging agronomic challenges. From 2005-2010, all four cropping systems had the same three-year rotation of corn–soybean–winter spelt/red clover [*Zea mays* L.–*Glycine max* (L.) Merr.–*Triticum spelta* L./*Trifolium pratense* L.]. Due to increasing weed populations, crop sequence in the HF and RT was changed in 2011 to a six-year rotation of corn—soybean—winter spelt—winter barley/buckwheat [*Hordeum vulgare* L./*Fagopyrum esculentum* Moench]—soybean—winter spelt/red clover. The LF and EWM systems maintained the original crop rotation (Table 1.1). Also in 2011, an experimental ridge tillage practice in the RT system was replaced by a combination of chisel plow and deep zone tillage (Table 1.1). Following positive response of spelt to increased compost application and seeding rate in the first six years of OCS (Caldwell et al. 2014), the EWM system began to receive compost application on spelt in 2011, and spelt seeding rate was increased to match EWM in all other systems (Table 1.1).

Nested Experiment. In 2014 and 2015, a nested experiment was conducted in the soybean phase of each crop rotation entry point. Soybean followed buckwheat (HF, RT) or corn (LF, EWM) in both years of the nested experiment. Soybean cv. 'Dares' (relative maturity 0.8, food grade, imperfect yellow hilum; Butterworks Farm, Westfield, VT, USA) was inoculated with Ndure (*Bradyrhizobium japonicum*, INTX Microbials, LLC, Kentland, IN, USA) and planted in 76 cm rows at 642,000 seeds ha^{-1} (2014) or 715,000 seeds ha^{-1} (2015) using a 4-row planter (John Deere, Moline, IL, USA). Soybean seeding rates were higher than conventional rates in order to hasten crop canopy closure and suppress weeds.

Table 1.1. Summary of OCS cropping system management, 2011-2015. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage.

System	HF	LF	EWM	RT
Crop rotation	C/r-S-SP-B/BU-S-SP/c	C-S-SP/c	C/r-S-SP/c	C-S-SP-B/BU-S-SP/op
Fertility inputs[a]				
Compost[b] (Mg ha^{-1})	3.4 (B), 1.1 (SP)	-	1.1 (SP)	3.4 (B), <2 (C)
P, K[c]	varied (C, SP)	-	-	-
Tillage[d]				
Moldboard plow	C, S, SP, B, BU	C, S	C, S, SP	-
False seedbed	-	-	S (if possible)	-
Deep zone till	-	-	-	C
Chisel plow	-	-	-	S, SP, B, BU
Weed control[e]				
Tine harrow	1-3	1-3	1-3	-
Inter-row cultivator	1-4	1-4	2-5	1-3

C corn, *S* soybean, *SP* spelt, *B* winter barley, *BU* buckwheat; *r* annual ryegrass, *c* red clover, *op* oat/Austrian winter pea mix.
[a] Application rates per season. All systems received low analysis starter fertilizer on corn.
[b] Composted poultry manure (5-5-3 N-P_2O_5-K_2O, Kreher's Enterprises, Clarence, NY, USA). Rates assume 14% moisture. EWM did not receive compost before 2011. RT received variable compost when necessary to supplement inadequate legume N.
[c] Organic fertilizers applied based on P and K soil tests.
[d] Tillage practices by crop. All systems also used secondary tillage (disc, roller harrow).
[e] Events per season in corn and soybean.

Weed Infestation Treatments. We used a split-split-plot randomized complete block design for the nested experiment. However, because our nested experiment took place in only one rotation entry point each year (2014, entry point A; 2015, entry point B), entry point was not included as a split-plot factor for analyses. Instead we considered weed infestation treatment to be the split-plot factor. Two weed infestation treatments (Standard Management and Weed Free) were implemented in sub-plots (3.0 m x 6.1 m) that were randomly located in each soybean main plot. Standard Management sub-plots received the same soybean management practices as the system in which they were located (Table 1.2). Weed Free sub-plots were hand weeded every 1-2 wk until mid-August in addition to receiving standard weed management practices (Table 1.2).

Table 1.2. Dates of management practices and sampling events in the nested experiment (2014-2015) in the Cornell Organic Grain Cropping Systems Experiment in Aurora, NY, USA. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, entry point A; 2015, entry point B.

Event	2014				2015			
Cropping system management	HF	LF	EWM	RT	HF	LF	EWM	RT
Tillage								
Moldboard plow	20 May	27 May	20 May	-	26 May	26 May	4 May	-
Chisel plow	-	-	-	20 May	-	-	27 May[b]	27 May[c]
Disc	27 May	27 May	27 May	27 May	4 Jun	4 Jun	4 May	4 Jun
Field cultivator	-	-	-	-	-	-	4 Jun	-
Roller harrow[a]	30 May	30 May	28 May 30 May	30 May	5 Jun	5 Jun	4 May 5 Jun	5 Jun
Soybean planting	30 May	30 May	30 May	30 May	5 Jun	5 Jun	5 Jun	5 Jun
Weed control								
Tine harrow	6 Jun	6 Jun	6 Jun	-	-	-	-	-
Inter-row cultivator	16 Jun 20 Jun 23 Jun 2 Jul	16 Jun 20 Jun 2 Jul	16 Jun 20 Jun 23 Jun 2 Jul 23 Jul	16 Jun 20 Jun 23 Jun 2 Jul	23 Jun 25 Jun 6 Jul 17 Jul	23 Jun 25 Jun 6 Jul 17 Jul	23 Jun 25 Jun 6 Jul 17 Jul 31 Jul	23 Jun 25 Jun 6 Jul 17 Jul
Treatment management	All Systems							
Hand weed every 1-2 wk (Weed Free)	27 Jun – 7 Aug				2 Jul – 6 Aug			
Sampling	All Systems							
Soil sampling	19 June				24 Jun			
Biomass sampling	18 Aug				14 – 15 Aug			
Soybean harvest	6 Oct				7 – 8 Oct			

[a] with or without cultimulcher tine attachment
[b] Chisel plow was used in EWM, 2015 to disrupt rhizomatous perennial weeds
[c] Chisel plow 2x in RT, 2015

Sampling.

Crop Growth Stage. Six (2014) or four (2015) soybean plants were randomly selected from the inner rows of Standard Management sub-plots, tagged, and observed for vegetative and reproductive growth stage during the growing season.

Biomass and Density. Soybean and weed aboveground biomass in each sub-plot were sampled in two 0.25 m^2 quadrats (76 cm x 33 cm) in mid-August of each year (Table 1.2). All stems rooted in the quadrat were clipped at soil level, separated by species, counted, oven-dried at 40 C for at least 2 wk, and weighed. Data from the two quadrats in each sub-plot were averaged before analyses.

Soybean Yield. Soybeans were harvested in October of each year (Table 1.2) from the inner two rows of each sub-plot using a plot combine that measured grain mass and moisture content (Almaco, Nevada, IA, USA). Soybean grain yields were standardized before analyses (g m^{-2} at 13% moisture), accounting for the area where soybean plants were removed during previous sampling (i.e., biomass quadrats).

Data Analysis.

Weed Abundance and Community Composition. In addition to directly measured weed responses (biomass and density), several derivative responses were calculated in each Standard Management sub-plot to describe weed abundance and community composition. Weed size (g $stem^{-1}$) was calculated as total weed biomass (g m^{-2}) divided by total weed density (stems m^{-2}) within each sub-plot. Species richness was determined as the number of weed species present per quadrat (species 0.5 m^{-2}). Species evenness describes the relative allocation of weed biomass or density among species and is calculated using the following equation:

$$\text{Evenness} = -\frac{\sum[P_i \times \ln(P_i)]}{\ln(S)} \qquad [1.1]$$

where P_i are the proportions of each weed species' biomass or density relative to the sub-plot total, and S is species richness of the sub-plot. Species evenness ranges from near 0 (one species highly dominant) to 1 (all species equally abundant).

Weed density, biomass, size, richness, and evenness were analyzed using mixed model ANOVA. Fixed effects were Year, System, and their interaction. Two random effects (Block, n=4; System-within-Block, n=16) were included in the model. Residuals were visually checked for homogeneity of variance. Weed density, biomass and size were ln(x+1) transformed to correct heteroscedasticity; back-transformed least square means are reported. Least square means were grouped at significant ($P<0.05$) factor levels using the Tukey method. All ANOVAs were performed in R version 3.2.0 (R Foundation for Statistical Computing, Vienna, Austria; R Development Core Team, 2015).

Effects of cropping system on weed community composition under Standard Management were analyzed using multivariate techniques in PC-ORD version 6.08 (MjM Software, Gleneden Beach, OR). We compared Standard Management weed communities between cropping systems using permutation-based analysis of variance (PerMANOVA) with Bray-Curtis distance measures (McCune and Grace 2002). Weed species occurring in less than two Standard Management sub-plots were omitted. A two-way factorial design (Year x System) was first used to test for overall effects. Statistical significance was estimated using a randomization procedure (5,000 runs). Then, pairwise comparisons at significant factor levels were tested manually using a one-way factorial design. Where necessary due to missing data, we used a repeated stratified random sampling procedure and reported mean F and P-values after 500 iterations (Peck 2010).

To elaborate on weed community differences identified by PerMANOVA, we performed a rank abundance of weed species in each cropping system and year. Density and biomass of dominant weed species (i.e., those making up 95% total biomass) were described.

Association of weed species with particular cropping systems was tested using Indicator Species Analysis (Dufrêne and Legendre 1997). Indicator values (IV) for each species were calculated by multiplying relative abundance by relative frequency within a cropping system. Indicator values range from 0 (not detected) to 100 (exclusive association). Significance of indicator values was estimated using a Monte Carlo procedure (5,000 runs) and considered significant when $P<0.1$. Data from each year were analyzed separately.

Soybean Performance. Soybean biomass, yield, and yield:biomass ratio were analyzed using mixed model ANOVA. Soybean yield:biomass ratio in each Standard Management and Weed Free sub-plot was calculated as soybean yield divided by soybean biomass. The yield:biomass ratio was not a true 'harvest index' because biomass and yield were measured at different times during the season; however, the ratio provides a relative measure of soybean resource allocation to vegetative and reproductive growth. Weed Free and Standard Management sub-plots were analyzed in a single model. Fixed effects were Year, System, Treatment, and their interactions. Three random effects (Block, n=4; System-within-Block, n=16; Entry Point-within-System-within-Block, n=32) were included in the model.

Weed-Soybean Competition. Competition intensity between weeds and soybean under Standard Management was quantified at the plot level using a "Competition Index". The Competition Index expresses soybean biomass loss or yield loss per unit weed density (g stem^{-1}) or biomass (g g^{-1}), and a greater value indicates greater weed-crop competition intensity. The Competition Index was calculated using the following equation:

$$\text{Competition Index} = \frac{S_{wf} - S_{sm}}{W_{sm}} \qquad [1.2]$$

where the numerator is soybean biomass or yield in the Weed Free treatment minus that in Standard Management (g m^{-2}), and the denominator is weed biomass (g m^{-2}) or density (stems m^{-2}) in the Standard Management treatment. Because two soybean measures (biomass, yield) and two weed measures (density, biomass) were used, four Competition Index values were calculated in each plot. Competition Index results were analyzed using mixed model ANOVA. Fixed effects were Year, System, and their interaction. Random effects were Block and System-within-Block.

Results and Discussion

Monthly mean temperatures during both soybean growing periods of the experiment (May – October 2014, 2015) were within 4 degrees C of the historical average (Figure 1). Precipitation in 2014 was similar to the historical average. In 2015, heavy spring rainfall (Figure 1) and poor drainage at the field site caused ponding in some plots in early June, which was accompanied by patchy soybean germination and slow early-season growth in all systems.

Weed Abundance. Weed density was greater in 2015 compared to 2014. Under Standard Management conditions, average weed density ranged from 26 to 117 stems m^{-2} and was lowest in EWM, intermediate in HF, and highest in LF and RT across both years (Table 1.3). Since the LF and EWM systems differed only in weed management, lower weed density in EWM than LF implied that the supplemental weed management practices (extra cultivations with precision equipment, false seedbed tillage before soybean, greater spelt seeding rate and compost application on spelt) have effectively reduced weed densities. Weed densities in our two-year experiment were greater than weed densities found in organic soybean by Delate and Cambardella (2004).

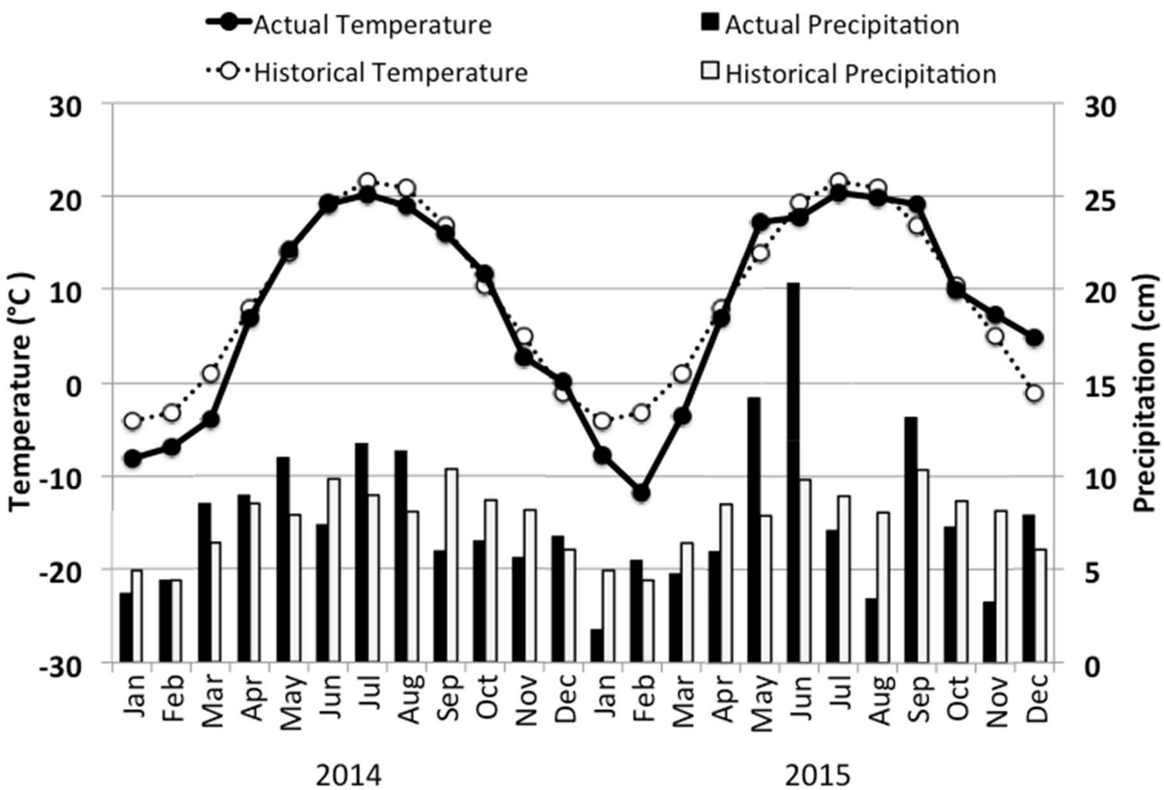

Figure 1.1. Monthly average temperature (lines) and total precipitation (bars) at the Musgrave Research Farm (42.73' N, 76.66' W), 2014-2015. Actual conditions (solid, black) are shown beside 30 yr historical averages (dotted, white). Data were accessed through the Northeast Regional Climate Center database (http://climod.nrcc.cornell.edu/).

Average weed biomass ranged from 12 to 69 g m^{-2} across systems and years (Table 1.3). However, there were no significant differences in weed biomass between cropping systems in either year (Table 1.3). Weed biomass in all systems was low compared with that reported in other long-term organic grain experiments (Davis et al. 2005, Menalled et al. 2001, Ryan et al. 2009), indicating that weed control in the OCS was relatively successful overall. Average weed size ranged from 0.25 to 1.56 g $stem^{-1}$ and did not differ by year or cropping system.

The HF system had similar weed abundance to LF and EWM, despite a history of greater poultry compost and mineral fertilizer inputs in the HF system. In contrast, weed abundance has been shown to increase with nutrient additions in other research, especially when nutrients are supplied in excess of crop demand (Blackshaw et al. 2003, Davis and Liebman 2001). Indeed, during the first six years of the OCS experiment, weed biomass was often greater in HF than LF (Caldwell et al. 2014).

Our data can be used to assess the efficacy of the 2011 crop rotation changes within the OCS, which were intended to correct increasing weed abundance in the HF and RT systems. In the two years of our nested experiment, weed density was similar in the HF and EWM systems and greater in RT than EWM. These results suggest that the new crop rotation was more effective at reducing weed abundance in the HF system than in the RT system, illustrating a need

Table 1.3. Results from ANOVA of weed density, biomass, and size, species richness and evenness under Standard Management. For density, biomass, and size, ANOVA was performed on ln(x+1) transformed values and back-transformed least square means are reported. Possible values of evenness range from near 0 (one species highly dominant) to 1 (all species equally abundant). HF High Fertility, LF Low Fertility, EWM Enhanced Weed Management, RT Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B.

System	Weed Density	Weed Biomass	Weed Size	Species Richness	Evenness Density	Evenness Biomass
	stems m^{-2}	g m^{-2}	g $stem^{-1}$	species 0.5 m^{-2}	unitless	
2014						
HF	**26 AB**	34	1.56	**6.2 ab**	0.91	0.67
LF	**56 A**	13	0.25	**6.0 ab**	0.73	0.54
EWM	**28 B**	16	0.59	**5.0 b**	0.82	0.59
RT	**69 A**	69	1.29	**9.8 a**	0.79	0.50
2015						
HF	**61 AB**	35	0.70	**5.9 bc**	0.77	0.52
LF	**117 A**	50	0.46	**7.8 b**	0.67	0.53
EWM	**28 B**	12	0.50	**3.0 c**	0.60	0.37
RT	**82 A**	19	0.35	**12.0 a**	0.88	0.59
				P value		
Year	**0.022**	0.909	0.098	0.386	0.119	0.422
System	**0.003**	0.233	0.122	**<0.001**	0.204	0.801
Year × System	0.193	0.079	0.153	**0.044**	0.184	0.517

Capital letters indicate system differences at $P<0.05$ averaged across years. Lowercase letters indicate system differences at $P<0.05$ within a year.

to further refine RT system weed management.

Weed Community Composition. Weed species richness in RT was greater than EWM in both years, and greater than all systems in 2015 (Table 1.3), suggesting that a greater number of weed species could survive RT management practices versus practices in other systems. The effect appeared to be exacerbated by unfavorable spring weather and poor soybean germination in 2015, which could suggest that under normal weather conditions, competition by the soybean limited weed species richness in the RT system. Lower species richness in EWM than LF in 2015 (Table 1.3) suggests that extra weed management practices in the EWM system have reduced weed community diversity in addition to weed abundance. The EWM management practices might be diminishing populations of weed species whose seedbanks or energy reserves are depleted by an intensive disturbance regimen. In contrast, McCloskey et al. (1996) found greater weed species diversity under plowed than minimum tillage plots. The minimum tillage plots in that experiment became dominated by a single species, *Bromus sterilis* L., which cannot germinate when seeds are buried by plowing (McCloskey et al. 1996).

Weed species evenness was not affected by cropping system, meaning that weed communities in all cropping systems were similarly homogenous (Table 1.3). Evenness was greater based on weed density than weed biomass (Table 1.3), reflecting a greater difference in weed community in the size of weeds than in the number of weeds.

In permutation-based analysis of variance (PerMANOVA), weed community composition based on density differed at the year by cropping system interaction level (Table 1.4). The weed community in RT differed from LF and EWM in both years, and LF differed from EWM in 2015 (based on density). Based on biomass, weed communities differed by year and by system, but not at the interaction level. The weed community in RT differed from LF and EWM across years, and HF differed from EWM across years (based on biomass). These results echoed and reinforced the results from ANOVA of weed species diversity. Differences in weed community composition between years might have been due to efficacy of in-season weed management based on weather conditions, legacy effects of crop rotation entry point, or spatial heterogeneity of the field site.

To elaborate on weed community differences identified by PerMANOVA, we performed a rank abundance of weed species in each cropping system and year. Density and biomass of dominant weed species (i.e., those making up 95% total biomass) are shown in Table 1.5. The number of dominant weed species ranged from 2 to 8 and was lowest in EWM in both years, reflecting lower weed species diversity compared to other systems.

Two summer annual species, *Ambrosia artemisiifolia* L. and *Setaria faberi* Herrm. were present in 7 out of 8 cropping system x year combinations, and in some cases were highly abundant. *Ambrosia artemisiifolia* L. accounted for 62% of the total biomass in the HF system in 2015 and *Setaria faberi* Herrm. accounted for 39% of total weed biomass in the EWM system in 2014 (Table 1.5). In the HF and RT systems in 2014, volunteer buckwheat (*Fagopyrum esculentum* Moench) accounted for over 40% of total weed biomass, but only 3% of weed density, showing the large size of buckwheat versus most other weed species.

Perennial weed species were also abundant in both years, particularly in the RT system.

Table 1.4. Results of PerMANOVA on weed density and weed biomass under Standard Management. Overall analysis was performed with a Year x System factorial design. Pairwise comparisons at significant factor levels were performed manually. Where necessary to correct for missing data (HF), a bootstrap random sampling procedure with 500 repetitions was used (Peck 2010) and mean *P*-value is reported. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B.

Factor	Weed Density				Weed Biomass	
		F	*P*		*F*	*P*
Year		**3.89**	**<0.001**		**3.20**	**<0.001**
System		**4.32**	**<0.001**		**2.21**	**0.002**
Year × System		**1.88**	**0.014**		1.48	0.089
	2014		2015		Years combined	
	F	*P*	*F*	*P*	*F*	*P*
HF vs LF	2.07	0.125	4.53	0.100	2.03	0.059
HF vs EWM	3.24	0.100	4.70	0.100	**2.74**	**0.011**
HF vs RT	2.29	0.152	2.34	0.100	1.78	0.063
LF vs EWM	0.96	0.454	**5.00**	**0.029**	0.80	0.589
LF vs RT	**2.10**	**0.033**	**8.32**	**0.028**	**2.05**	**0.015**
EWM vs RT	**3.83**	**0.029**	**6.55**	**0.026**	**2.79**	**0.002**

For example, *Cirsium arvense* (L.) Scop. accounted for 15 and 20% of total weed biomass in the RT system in 2014 and 2015, respectively. Five out of eight dominant weed species in the RT system in 2015 were perennial. However, some perennial weeds were also highly abundant in other cropping systems. For example, *Sonchus arvensis* L. was the second most abundant species in the HF system in both years accounting for 19 and 15% of total weed biomass in 2014 and 2015, respectively. This species was also highly abundant in the LF system in 2014 (56% of total weed biomass). *Calystegia sepium* (L.) R. Br. accounted for 6 and 31% of total biomass in the LF system and 11 and 84% of total biomass in the EWM system in 2014 and 2015, respectively.

Indicator Species Analysis showed that eleven weed species were indicators of cropping systems at the $P<0.1$ level (Table 1.6). The EWM system had one instance of species indication, HF and LF each had three, and RT had eight instances of species indication (counting years separately). Two species (*Chenopodium album* L. and *Fagopyrum esculentum* Moench) consistently indicated the RT system in both years. Two other species were "unfaithful" indicators across years; *Calystegia sepium* (L.) R. Br. indicated EWM in 2014 and LF in 2015; *Setaria faberi* Herrm. indicated RT in 2014 and LF in 2015. In addition to *Calystegia sepium* (L.) R. Br., other perennial indicator species were *Taraxacum officinale* G.H. Weber ex Wiggers in HF (2014) and *Cirsium arvense* (L.) Scop. in RT (2015). Twice as many species were indicators in 2015 compared with 2014, suggesting more heterogeneous weed community in 2015 that might have been related to patchy soybean germination leaving space available for weed growth.

The large number of species indicating RT is in accordance with both high species richness and a distinct weed community in this system. Together, these results imply that reducing tillage had the most dramatic influence on weed community of any management practice under examination.

Table 1.5. Rank abundance of dominant weed species in each cropping system under Standard Management. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B. Asterisks (*) denote perennial species.

System	2014					2015				
	Species	%D[a]	D	%B	B	Species	%D	D	%B	B
HF	*Fagopyrum esculentum* Moench	3	1	41	19	*Ambrosia artemisiifolia* L.	42	27	62	35
	Sonchus arvensis L.*	20	5	19	9	*Sonchus arvensis* L.*	18	12	15	8
	Ambrosia artemisiifolia L.	25	7	11	5	*Sinapis arvensis* L.	8	5	12	7
	Taraxacum officinale[b]*	5	1	10	5	*Cirsium arvense* (L.) Scop.*	7	5	3	2
	Sinapis arvensis L.	5	1	8	4	*Setaria faberi* Herrm.	5	3	3	1
	Solanum carolinense L.*	3	1	4	2					
	Setaria faberi Herrm.	3	1	4	2					
LF	*Sonchus arvensis* L.*	10	7	56	9	*Ambrosia artemisiifolia* L.	14	17	31	19
	Setaria faberi Herrm.	42	31	26	4	*Calystegia sepium* (L.) R. Br.*	52	63	31	19
	Calystegia sepium (L.) R. Br.*	9	7	6	1	*Setaria faberi* Herrm.	17	21	27	16
	Ambrosia artemisiifolia L.	9	7	5	1	*Polygonum persicaria* L.	6	6	7	4
	Setaria glauca (L.) Beauv.	21	16	4	1					
EWM	*Setaria faberi* Herrm.	49	15	39	7	*Calystegia sepium* (L.) R. Br.*	76	23	84	12
	Ambrosia artemisiifolia L.	10	3	26	5	*Ambrosia artemisiifolia* L.	15	5	14	2
	Sinapis arvensis L.	7	2	21	4					
	Calystegia sepium (L.) R. Br.*	21	7	11	2					
RT	*Fagopyrum esculentum* Moench	3	2	42	47	*Ambrosia artemisiifolia* L.	11	10	30	13
	Setaria faberi Herrm.	18	13	23	26	*Cirsium arvense* (L.) Scop.*	19	17	20	9
	Cirsium arvense (L.) Scop.*	3	2	15	17	*Setaria glauca* (L.) Beauv.	14	12	17	8
	Chenopodium album L.	21	15	8	8	*Solanum carolinense* L.*	5	5	13	6
	Amaranthus spp.	1	1	6	7	*Setaria faberi* Herrm.	6	6	9	4
	Sinapis arvensis L.	3	2	3	3	*Rumex crispus* L.*	1	1	2	1
						Calystegia sepium (L.) R. Br.*	4	4	2	1
						Cyperus esculentus L.*	2	2	2	1

[a] Percentages and absolute values of weed density (D, stems m^{-2}) and biomass (B, g m^{-2}) are presented. Tables includes species accounting for at least 95% of total weed biomass.
[b] *Taraxacum officinale* G.H. Weber ex Wiggers

Table 1.6. Results from Indicator Species Analysis conducted on weed biomass and weed density under Standard Management. Instances where an indicator value was significant (P<0.1) are reported. P-values were simulated using a Monte Carlo procedure with 5000 runs. Indicator Values (IV) range from 0 (no indication) to 100 (perfect indication). HF High Fertility, LF Low Fertility, EWM Enhanced Weed Management, RT Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B. Asterisks (*) denote perennial species. **Bold font** denotes indicators significant at the P<0.05 level.

	2014					2015				
Species	System	Biomass		Density		System	Biomass		Density	
		IV	*P*	IV	*P*		IV	*P*	IV	*P*
Ambrosia artemisiifolia L.	-	-	-	-	-	**HF**	**-**	**-**	**46.9**	**0.038**
Calystegia sepium (L.) R. Br. *	**EWM**	**66.8**	**0.037**	-	-	**LF**	**57.9**	**0.023**	**70.6**	**<0.001**
Chenopodium album L.	**RT**	**93.7**	**0.006**	**88.2**	**0.005**	RT	-	-	63.0	0.061
Cirsium arvense (L.) Scop. *	-	-	-	-	-	**RT**	**85.2**	**0.024**	**78.5**	**0.015**
Fagopyrum esculentum Moench	RT	-	-	56.2	0.091	**RT**	**75.0**	**0.029**	**75.0**	**0.032**
Hordeum vulgare L.	-	-	-	-	-	**RT**	**75.0**	**0.030**	**75.0**	**0.029**
Poa spp.	-	-	-	-	-	**RT**	**100.0**	**0.002**	**100.0**	**0.003**
Polygonum persicaria L.	-	-	-	-	-	LF	62.0	0.083	54.4	0.072
Setaria faberi Herrm.	RT	66.6	0.086	-	-	**LF**	**75.6**	**0.041**	**70.4**	**0.028**
Sinapis arvensis L.	-	-	-	-	-	HF	80.4	0.075	-	-
Taraxacum officinale[a] *	**HF**	**66.7**	**0.027**	**66.7**	**0.030**	-	-	-	-	-

[a] *Taraxacum officinale* G.H. Weber ex Wiggers

The relative occurrence of perennial weeds among systems was not consistent across the two years of our experiment. Perennial weeds made up 33, 62, 11, and 15% of total weed biomass in the HF, LF, EWM, and RT systems respectively in 2014; and 3, 31, 84, and 39% respectively in 2015 (Table 1.5). The RT system favored one perennial species (*Cirsium arvense* (L.) Scop.), and the LF and EWM systems favored another perennial species (*Calystegia sepium* (L.) R. Br.). Gruber and Claupein (2009) found *Cirsium arvense* (L.) Scop. density, biomass, and seedbank to increase with a chisel plow versus more intense primary tillage methods. However, these authors also found an interaction effect in which a secondary shallow stubble tillage reduced *Cirsium arvense* (L.) Scop. density in most primary tillage treatments, but increased *Cirsium arvense* (L.) Scop. density in the chisel plow treatment.

Other researchers have found reduced tillage systems to favor grass weed species (Davis et al. 2005, McCloskey et al. 1996, Menalled et al. 2001). However, the reduced tillage systems in these experiments were not organic, so the selective "filters" imposed by management were different than in our experiment. The mechanisms of tillage in hindering or promoting particular weed species warrant further examination.

The occurrence of volunteer crops (winter barley and buckwheat) in the OCS weed communities highlights the likelihood of unintended consequences in agricultural management. Winter barley and buckwheat were introduced in the HF and RT rotations in order to reduce weed problems, but they also unexpectedly changed weed communities by self-seeding. Many factors might have contributed this outcome including variety selection, weather conditions, harvest equipment functionality, or scheduling conflicts with other farm management activities around the time of harvest.

Soybean Performance. Under Standard Management, average soybean biomass by cropping system ranged from 446 – 625 g m^{-2} in 2014 and 241 – 422 g m^{-2} in 2015 (Table 1.7). Soybean biomass was not affected by cropping system in 2014. In 2015, soybeans in LF accumulated less biomass than those in RT (P<0.05), whereas HF and EWM were intermediate.

Table 1.7. Results from ANOVA of soybean biomass, yield, yield:biomass ratio, and Competition Indexes under Standard Management and Weed Free. Least square means followed by the same letter are not different at $P<0.05$. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B.

	Soybean Biomass		Soybean Yield		Soybean Yield:Biomass		SM Competition Index			
							Soybean Biomass		Soybean Yield	
	SM[a]	WF[a]	SM	WF	SM	WF	vs WD	vs WB	vs WD	vs WB
	g m^{-2}		g m^{-2}		g g^{-1}		g $stem^{-1}$	g g^{-1}	g $stem^{-1}$	g g^{-1}
2014										
HF	480	625	**303 Ab**	**348 Aa**	0.67	0.56	6.76	1.53	1.84	1.05
LF	527	483	**287 ABb**	**313 ABa**	0.55	0.65	-1.13	-4.22	0.77	3.90
EWM	446	485	**252 Bb**	**252 Ba**	0.58	0.52	0.92	0.20	0.06	-0.11
RT	475	459	**288 Ab**	**331 Aa**	0.62	0.75	-0.51	-4.45	0.58	1.68
2015										
HF	**320 *AB***	**385 *AB***	**185 Ab**	**194 Aa**	0.62	0.54	0.80	0.30	-0.03	-0.60
LF	**241 *B***	**244 *B***	**170 ABb**	**187 ABa**	0.71	0.78	0.03	0.22	0.16	0.41
EWM	**247 *AB***	**285 *AB***	**162 Bb**	**155 Ba**	0.66	0.58	1.72	2.89	-0.18	1.12
RT	**388 *A***	**422 *A***	**183 Ab**	**225 Aa**	0.53	0.54	-0.29	-12.67	0.67	12.93
	P value									
Year	**<0.001**		**<0.001**		0.721		0.680	0.947	0.071	0.605
System	0.064		**0.011**		0.507		0.160	0.288	0.386	0.433
Treatment	0.234		**0.004**		0.807					
Yr × Sys	0.039		0.189		0.087		0.271	0.600	0.206	0.360
Yr × Trt	0.878		0.328		0.569					
Sys × Trt	0.266		0.115		0.207					
Yr×Sys×Trt	0.710		0.803		0.903					

Capital, italic letters indicate system differences within a year, averaged across treatments.
Capital letters indicate system differences averaged across treatments and years.
Lowercase letters indicate treatment differences averaged across systems and years.
[a] *SM* Standard Management, *WF* Weed Free, *WD* weed density, *WB* weed biomass
[b] per unit weed density or biomass

Soybean grain yields ranged from 252 – 348 g m^{-2} in 2014 and 155 – 225 g m^{-2} in 2015 (Table 1.7). Compared with historical soybean yields in the OCS trial (2005-2010), yields in our experiment were average to above average in 2014, but below average in 2015 (Caldwell et al. 2014). Lower yields in the second growing season appeared to be caused by unfavorable weather. High precipitation in June 2015 and poor drainage at the field site appeared to limit soybean germination and early growth, and then low precipitation in August 2015 might have limited later growth and pod fill (Figure 1.1). Across both years, EWM had lower soybean yields than both HF and RT (P<0.05), whereas LF yields were intermediate. EWM soybeans lagged behind HF and RT in vegetative growth stage during both growing seasons (Figure 1.2).

Soybean yield:biomass ratio in the experiment ranged from 0.53 to 0.78, and was not affected by year, cropping system, or weed treatment. The year by system interaction effect on soybean yield:biomass ratio was marginally significant (P=0.087).

Weed-Soybean Competition.

ANOVA. Soybean yield was reduced by weeds across years and systems, with Standard Management showing an average 9% yield loss relative to Weed Free conditions (P=0.004, Table 1.7). In contrast, soybean biomass was not affected by the presence of weeds (P=0.234). Soybean yield might have been affected more strongly by weed competition than soybean biomass if weed nutrient uptake caused crop nutrient deficiency to onset during pod fill.

A system by treatment interaction effect on soybean biomass or yield would indicate that soybean response to Standard Management weed levels differed among cropping systems. However, yield differences between Weed Free and Standard Management were not different among cropping systems (System × Treatment, P=0.115). EWM yields under Weed Free conditions tended to be lower or similar to those under Standard Management.

Competition Indexes. Four Competition Indexes were calculated in each system plot each year (soybean biomass or yield loss per unit weed density or biomass). Average Competition Indexes by cropping system and year ranged from -12.67 to 12.93 g $stem^{-1}$ or g g^{-1} (Table 1.7), which was a much wider range than expected. Many of the average Competition Indexes were negative (indicating greater soybean performance with greater weed abundance), even in some cases where average Weed Free soybean yield or biomass were greater than Standard Management. Low weed abundance in some SM treatments likely contributed to this result. Another possible contributing factor was variability in soybean and weed growth at the sub-plot level, which was compounded, not corrected for, when calculating the Competition Indexes. There were no significant effects on any Competition Index in the ANOVA models, likely due to large variability. Although the Competition Index is theoretically a precise indicator of weed-crop competition intensity, the approach should be considered cautiously in situations where field variability is high.

The EWM system had the lowest soybean yields, but also the lowest weed density in both years of our two-year experiment. Furthermore, EWM yields under Weed Free conditions tended to be lower or similar to Standard Management yields. These results imply that overall yield potential of EWM was lower than other systems, and that weeds were likely not an important limiting factor in determining EWM soybean yield. Low yields in EWM were unexpected, considering that during the first six years of the OCS experiment (2005-2010), soybean yields in EWM were among the highest (Caldwell et al. 2014). Soil structure damage from early false seedbed tillage or intensive cultivation, and/or soybean root damage during cultivation could have contributed to low EWM soybean yields in 2014 and 2015 (B Caldwell, pers communication). The LF and EWM systems have a history of low nutrient input, and soil nutrient depletion could also be limiting yield potential in these systems (B Caldwell, C Mohler, pers communication; see Chapter 2).

The RT system in our experiment had the greatest weed density and species richness, most indicator weed species, and a weed community distinct from both LF and EWM. However, RT soybean yields were among the highest in our experiment, demonstrating that high weed abundance and diversity is not necessarily associated with low yield. These results demonstrate an apparent crop tolerance of weeds in the RT system in our experiment, echoing organic systems in other long-term trials (Davis et al. 2005, Delate and Cambardella 2004, Hiltbrunner et al. 2008, Ryan et al. 2009, 2010a), and suggesting that reducing tillage in organic systems might enhance characteristics of the soil environment that promote crop tolerance of weeds. Our work supports the idea that reduced tillage in organic systems could be extremely beneficial. Further research should focus on clarifying best management practices to mitigate the risks currently associated with reducing tillage in organic systems.

The purpose of this research was to characterize weed community structure and soybean performance in a long-term organic cropping systems experiment. In our two-year nested experiment, soybean yields were lowest in the EWM system where a history of intense and frequent soil disturbance resulted in relatively low weed abundance. Because yield loss due to weeds did not differ among cropping systems, we cannot draw conclusions about management practices or system properties influencing weed-crop competition intensity. However, our results do suggest that intensive mechanical weed control, though effective in reducing weed abundance and diversity, might also reduce soil production capacity.

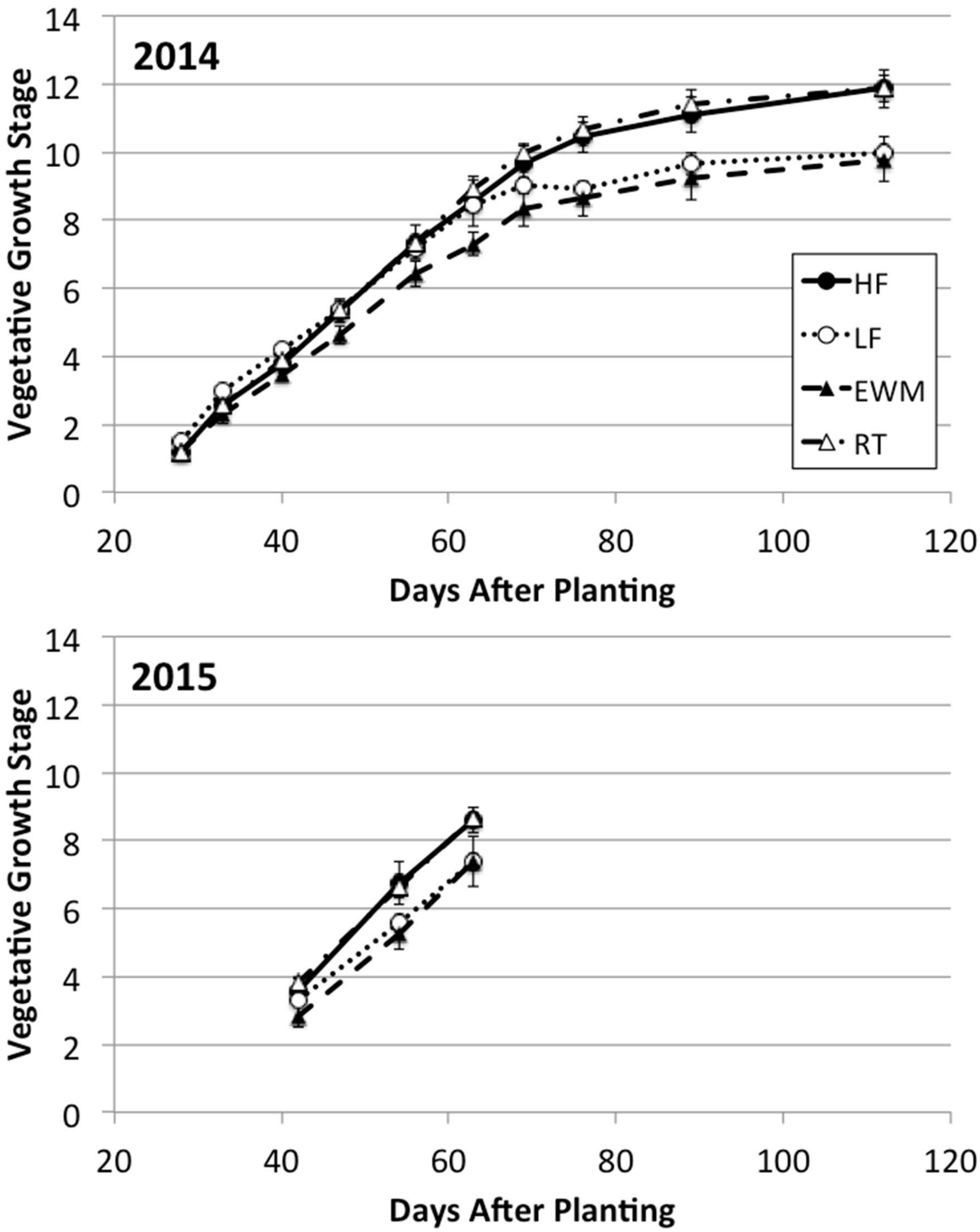

Figure 1.2. Soybean vegetative growth stages under Standard Management during 2014 (top) and 2015 (bottom). Bars show one standard error. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B.

CHAPTER 2

BELOWGROUND DRIVERS OF COMPETITION: SOIL ENVIRONMENT

Abstract

Weed competition with corn has been shown to be less intense in organic than conventional cropping systems in some circumstances. However, little research has been conducted on how different types of organic management might affect weed-crop competitive relationships, especially in legume crops. In 2014 and 2015, weed-soybean competition was quantified by measuring soybean biomass and soybean grain yield across a gradient of weed abundance in a long-term experiment that compared four organic cropping systems: (i) High Fertility (HF), (ii) Low Fertility (LF), (iii) Enhanced Weed Management (EWM), and (iv) Reduced Tillage (RT). We used a split-plot randomized complete block design with cropping system as main plots and three weed abundance sub-plots: (i) Weed Freed (WF), (ii) Standard Management (SM), and (iii) Supplemented Seedbank (SS). Non-linear regression showed that the relationship between soybean and weed abundance differed between cropping systems, mainly due to differences in weed-free soybean production capacity. In general, soybean biomass and yield were greater in the HF and RT systems than the LF and EWM systems. Cropping system management history affected extractable nutrients, organic matter, and soil structure. Weed-free soybean biomass and competition intensity were positively associated with several soil indicators in both correlation and Partial Least Squares Regression analysis, particularly inorganic N, NO_3^-, P, K, Ca, total soil C, and respiration. We did not find support for our hypothesis that weed-soybean competition would be negatively correlated with soil indicators. However, we demonstrated that management differences among organic cropping systems can affect important soil chemical and biological properties associated with soybean production capacity and weed-soybean competition intensity. More research is needed to disentangle the effect of soil properties on weed-crop competition and to determine the potential for interactions with crop type (e.g. corn vs. soybean).

Introduction

Increasing the relative competitive ability of crops against weeds is an important weed management strategy (Bastiaans et al. 2008). Organic cropping systems can achieve similar yields to conventional systems despite greater weed abundance, suggesting an apparent crop “tolerance” to weeds under organic management (Davis et al. 2005, Delate and Cambardella 2004, Hiltbrunner et al. 2008) that could be a promising model for reducing the impacts of weeds on crops.

Means by which soil and crop management might contribute to crop tolerance of weeds have recently been investigated in a long-term cropping systems trial at the Rodale Institute. A manure-based and a legume-based organic system were shown to have increased weed-free yield capacity and decreased weed-crop competition intensity in corn versus a conventional system managed without manure or legumes (Ryan et al. 2009, 2010a). Both increased weed-free yield capacity and decreased weed-crop competition intensity were thought to contribute to apparent crop tolerance of weeds in the organic systems.

Smith et al. (2010) proposed the Resource Pool Diversity Hypothesis (RPDH) as a possible explanation for apparent crop tolerance of weeds in organic cropping systems. The authors proposed that “soil resource pools” in agricultural systems are formed by decomposing crop residues, green and animal manures, and compost inputs, as well as inputs of mineral fertilizers. More diverse inputs might form more diverse soil resource pools, which in turn decrease weed-crop competition intensity by allowing resource partitioning among weeds and crops.

The RPDH assumes that the severity of weed competition depends on the degree to which crops and weeds are partitioning essential resources. If crops and weeds differ slightly in their resource requirements, and diverse resources are available to serve both weed and crop needs, this could expand the overall production capacity or “niche space” of the soil. This concept builds on the concept of niche differentiation in the ecological literature, expanding the concept to agricultural systems where soil properties and resource pools can be affected by management.

High soil nutrient levels can exacerbate weed-crop competition in cases where weed species access and accumulate nutrients more readily than crops (Di Tomaso 1995). Importantly, the RPDH proposes that weed-crop competition is contingent on the *nature* of soil resource pools in addition to their size.

Ryan et al. (2009) found support for parts of the RPDH in a long-term cropping systems trial in Pennsylvania. The authors found differences in corn-weed competitive relationships between organic and conventional systems. In a long-term experiment, organic systems attained similar corn yields to the conventional system despite greater weed abundance. This was partially explained by a greater overall crop yield potential in the organic soils, which was correlated with increased active carbon. Active carbon is an easily measured, labile pool of soil organic carbon associated with small-sized particulate organic matter that may serve as a slow-release nutrient source (Culman et al. 2012).

In Maryland, soils from organic systems with history of animal and green manure addition had greater nitrogen (N) mineralization potential and labile organic matter carbon (C) and N contents versus soils from conventional systems using synthetic fertilizers (Spargo et al. 2011). This research supported the notion of increased ‘resource pools’ with organic addition. N mineralization potential, labile organic C and N all tended to increase with longer organic crop rotation and greater manure or legume input (Spargo et al. 2011). A greenhouse experiment using soils from the same trial explored crop and weed resource partitioning by measuring overyielding in controlled corn-weed mixtures in an organic and a conventional soil. This experiment found inconsistent evidence for resource partitioning in organic and conventional soil (Poffenbarger et al. 2015).

“Soil resource pool diversity”, which was not clearly defined by Smith et al. (2009), needs a more specific definition in order to further study the RPDH. In this research, we examined soil extractable nutrients, organic matter, and structure as aspects of the soil environment that might be related to resource pool composition and function. Our work provides an opportunity to test the utility of these soil measurements in describing soil resource pool diversity.

Soil extractable nutrient pools vary in their magnitude, specific forms of mineral nutrients present (i.e., nitrate-N vs. ammonium-N), and their availability over time, temperature, and moisture gradients. Soil pH, cation and anion exchange capacity, texture, structure, mineralogy, organic matter lability, location, and nutrient content, plant-microbe associations, and many other factors also influence nutrient availability and uptake by plants. Soil nutrient availability can be affected by organic inputs to the soil, and different nutrient inputs, forms, can influence plant growth (Velthof et al. 1998).

Organic inputs to soil first enter the free or light particulate organic matter fraction of soil (fPOM) (Marriott and Wander 2006). As organic substances decompose further, they are incorporated into soil aggregates in the occluded particulate organic matter fraction (oPOM). Along the way, decomposing organic inputs are also reflected directly in extractable soil nutrient contents and overall soil organic matter. However, labile fractions of organic matter such as fPOM, oPOM, and active carbon often increase more quickly than total soil organic matter. The C:N ratio of organic material (including fPOM and oPOM fractions), which is influenced by management, is considered an indicator of organic matter quality and influences the speed of microbial decomposition (Heal et al. 1997).

A long-term experiment in Maryland found that labile organic matter fractions (particulate organic matter C and N as a fraction of total soil C and N) tended to increase with longer crop rotation (Spargo et al. 2011). Particulate organic matter C:N was lower (an indicator of higher quality) in the six-year versus the two-year rotation. The authors attributed soil organic matter enrichment in the three-year system to frequent manure application, and in the six-year system to greater residue inputs and tillage reduction during the 3 yr alfalfa forage.

Soil respiration reflects overall biological activity of the soil (Moebius-Clune et al. 2016). Microbial activity is related to many important soil functions, such as organic matter decomposition and mineralization of soil nutrients. Plant-microbial associations can assist in soil resource partitioning among plants of differing species (Smith et al. 2010). However, respiration measures overall soil microbial activity and cannot differentiate between microbial communities or describe their functions.

Aggregate stability measures the soil's ability to hold aggregate structure under water, wind, and mechanical erosive forces. In general, aggregate stability is promoted by maintaining living plant roots in the soil, reducing tillage, and adding fresh organic materials that stimulate fungal activity (Moebius-Clune et al. 2016, Oades 1984). Recent work has argued that physical protection inside soil aggregates is a major factor in soil organic matter turnover or retention rates (Lehmann and Kleber 2015). Thus, aggregate stability could be related to soil resource pools in that stable aggregates could sequester organic matter more readily. Soil organic matter protected within aggregates would be less available for microbial decomposition and plant nutrient availability.

We performed a two-year nested experiment at the Cornell Organic Grain Cropping Systems Experiment (OCS) in central New York State, which compared four organic grain cropping systems that varied in nutrient inputs, weed management, and tillage practices (Caldwell et al. 2014). Our objectives in this chapter are to (1) quantify weed-soybean competitive relationships in soils with varying organic management histories, (2) characterize soil property differences between cropping systems, and (3) assess relationships between weed and soybean growth, weed-free soybean yield capacity, weed-soybean competition intensity, and aspects of the soil environment that might be related to soil resource pool composition and function. In this chapter, the soil environment is examined in three categories of indicators: (1) extractable nutrients; (2) organic matter; (3) soil structure. We hypothesized that soybean production capacity would increase and competition intensity would decrease with increasing extractable nutrients, quantity and quality of organic matter, and improved soil structure.

Materials and Methods

Experiment. OCS location, experimental design, cropping systems, and field operations during the experiment (2014-15) are described in Chapter 1.

Treatments. In 2014 and 2015, three weed-level treatments (Standard Management, Weed Free, and Supplemented Seedbank) were implemented in each system to establish a gradient of weed abundance across which weed-soybean competition could be quantified. The Standard Management treatment demonstrated weed-soybean interactions under normal cropping system management. The Weed Free treatment demonstrated soybean production capacity in the absence of weeds. The Supplemented Seedbank treatment served to ensure a high level of weed abundance for assessing competition, and to standardize weed community composition among the cropping systems. Treatments were implemented in sub-plots (3.0 m x 6.1 m) placed randomly within each soybean plot. Treatment was considered a split-plot factor within cropping system.

Standard Management sub-plots received the same soybean management as the system in which they were located. Weed Free sub-plots were hand weeded every 1-2 wk during the early growing season in addition to standard weed management practices. Supplemented Seedbank sub-plots received a mix of weed species sown by hand immediately after soybean planting: *Amaranthus retroflexus* L.; *Ambrosia artemisiifolia* L.; *Avena fatua* L.; *Chenopodium album* L.; *Cirsium arvense* (L.) Scop. (2014 only); *Digitaria sanguinalis* (L.) Scop.; *Echinochloa crus-galli* (L.) Beauv.; *Setaria faberi* Herrm.; *Sinapis arvensis* L.; *Solanum carolinense* L. (2014 only). Target sowing rates were 300-1000 seeds m^{-2} for each species. Following poor establishment of weed seeds in 2014 (V&J Seed Farms, McHenry, IL, USA), the Supplemented Seedbank treatment was intensified in 2015 by lifting tractor implements to avoid standard weedings, and a different seed source was used (Azlin Seed Service, Leland, MS, USA).

Sampling.

Biomass, Density, and Yield. Soybean and weed aboveground biomass, density, and soybean yield sampling are described in Chapter 1.

Soil. A range of biological, chemical, and physical soil indicators were analyzed in each cropping system to (1) describe long-term effects of system management on soil properties and (2) investigate links between management-induced soil properties, soybean performance and weed-soybean competition intensity. Soil samples were analyzed for extractable macro- and micro-nutrients, organic matter by loss on ignition, total soil carbon and nitrogen, free and occluded particulate organic matter, inorganic N, N mineralization potential, active carbon, wet aggregate stability, and respiration.

Soil was sampled at the system plot level on 19 June 2014 and 24 June 2015. Twelve cores of 2 cm diameter and 20 cm depth were collected and composited in each system plot (three sub-plots x four cores each). Field-moist soil was sub-sampled for analysis of inorganic N and N mineralization potential. Remaining soil was air-dried and stored in paper bags at room temperature until further analysis.

Field-moist soil samples were stored in a cooler on ice until processing, which began within 4h of sample collection. Inorganic N (InorgN) and N mineralization potential were measured following Drinkwater et al. (1996). To extract inorganic N, field-moist soils were shaken for 1h in 2M KCl, centrifuged, and the supernatant was filtered and frozen. Nitrate and ammonium in thawed extracts was measured on a microplate reader. For nitrate, duplicate 10 μL aliquots of extracts were mixed with 160 μL vanadium cocktail (50 parts saturated vanadium (III) chloride solution, 3.3 parts 2% sulfanilamide solution, 3.3 parts 0.2% N-(1-naphthyl)-ethylenediamine dihydrochloride solution, 400 parts diH_2O) in wells of a 96-well plate. Plates were incubated at 37 C for 2 hr and absorbance was measured at 540 nm on a microplate reader (BioTek Instruments, Inc., Winooski, Vermont, USA). For ammonium, duplicate 100 μL aliquots of extracts were mixed with 50 µL color reagent (1 part sodium salicylate and nitroprusside solution [8.5g sodium salicylate and 63.9 mg sodium nitroprusside dihydrate in 50 mL diH_2O]; 1 part 0.3 mol L^{-1} NaOH; 1 part diH_2O) and 20 µL oxidation reagent (0.1 g dichloroisocyanuric acid sodium salt dihydrate in 100 mL diH_2O) in wells of a 96-well plate. Plates were incubated at 21 C for 30 min and absorbance was measured at 660 nm. Absorbance was converted to NO_3 or NH_4 concentration based on calibration standards on each plate (R^2 > 0.995). Results are reported as µg per g dry soil.

To measure N mineralization potential (Nmin), field-moist soil was incubated in di-H_2O at 30 C for 7 d in an oxygen-free environment (tubes were purged with N_2 gas and sealed). Inorganic N was then extracted, frozen and analyzed as before. N mineralization potential was calculated as final NH_4 minus initial NH_4 concentration.

Free and occluded particulate organic matter (fPOM, oPOM) were fractionated from air-dried soil based on size and density (Marriott and Wander 2006). Triplicate 40 g subsamples of soil were shaken for 1 h at 100 rpm with 75 mL sodium polytungstate (1.7 g cm^{-3}) and allowed to settle for 24 h. The free light fraction (fPOM) was aspirated from the top of the solution, rinsed, oven dried, and weighed as free particulate organic matter. The remaining heavy fraction was rinsed, shaken for 1 h in 150 mL 10% sodium hexametaphosphate (to disperse soil aggregates), and shaken/rinsed 6 – 12 times in diH_2O through a 53 micron mesh filter. Occluded particulate organic matter (oPOM) was separated from sand and gravel using a decanting technique, oven dried, and weighed. C and N contents of each POM fraction, as well as C and N contents of total soil, were analyzed on a dry combustion auto-analyzer (LECO Corporation, Saint Joseph, MI, USA). Free and occluded particulate organic matter were reported as g fPOM- or oPOM-C or -N per kg dry soil. The C:N ratio of each fraction was also reported.

Active carbon, wet aggregate stability, and respiration were analyzed in February and March 2016 following Cornell Soil Health Test protocols (Moebius-Clune et al. 2016). For active carbon, air-dried soil was sieved to 2 mm. Duplicate soil subsamples (2.5 g) were shaken for 2 min with 20 mL 0.02 M $KMnO_4$ and allowed to settle for 8 min. Absorbance at 550 nm was measured using a hand-held colorimeter and converted to active carbon (mg kg^{-1}) against a standard calibration curve (Culman et al. 2012).

For wet aggregate stability, soil aggregates (0.25 – 2.0 mm in size) were separated from air-dried soil using a shaker and series of stacked sieves. Approximately 30 g of aggregates were spread thinly on a 0.25 mm sieve and placed below a rainfall simulator for 5 min. Failed aggregates (soil passing the sieve) were collected, oven-dried and weighed. Soil remaining on the sieve was then rinsed vigorously to isolate stones, which were oven-dried and weighed. Wet aggregate stability was calculated as the weight of stable aggregates (weight of sample minus the weight of failed aggregates + stones) divided by the weight of sample and expressed as a percent.

Soil respiration was measured in a 4 d aerobic incubation. First, air-dried soil was sieved to 8 mm. Duplicate soil subsamples (20.00 g) were placed in glass jars along with a beaker of 9 ml 0.5 M KOH which served as a CO_2 trap. Soil was wetted to field capacity and then jars were sealed and allowed to incubate for 4 d at room temperature. After 4 d, electrical conductivity of the KOH was measured with a handheld probe. Respiration (g CO_2 kg $soil^{-1}$) was calculated using initial KOH conductivity, final KOH conductivity of samples and blanks, and conductivity of a saturated solution (0.25 M K_2CO_3).

Subsamples of air-dried soil were submitted to the Cornell Nutrient Analysis Laboratory (Ithaca, NY, USA) on 29 February 2016 for analysis of organic matter-loss on ignition (OM-LOI) and extractable nutrients. Macro- and micro-nutrients (P, K, Al, Ca, Fe, Mg, Mn, Zn) were extracted using the original Morgan protocol.

Data Analysis

Weed-Soybean Competition Modeling. Weed-crop competition was quantified in each cropping system using data from the three weed-level treatments (Weed Free, Standard Management, Supplemented Seedbank). Years were analyzed separately due to differences between years. The relationship between soybean production (biomass and yield) and weed abundance (biomass and density) was quantified using a modified rectangular hyperbola model (Ryan et al. 2009):

$$Y_c = \frac{\frac{1}{a_0}N_c}{1+i_w N_w} \qquad [2.1]$$

where Y_c is crop biomass or yield (g m^{-2}); a_0 is the reciprocal of weed-free individual crop plant biomass or yield (plant g^{-1}); N_c is crop density (a constant, plants m^{-2}); N_w is weed biomass (g m^{-2}) or density (stems m^{-2}); and i_w is fractional crop biomass or yield loss per unit weed biomass (m^2 g^{-1}) or density (m^2 stem^{-1}) – the slope of the model as N_w approaches zero. Because crop density did not vary by year cropping system, weed treatment, or their interactions (ANOVA of log(density), results not shown), the constant N_c was calculated once for each year, averaged across cropping systems.

The fraction N_c/a_0 is estimated crop biomass or yield capacity under weed-free conditions. Since N_c was constant between cropping systems in each year, values of a_0 reflect weed-free production capacity; a greater a_0 value indicates a lower weed-free production capacity. The i_w parameter is the intensity of weed-crop competition; a greater i_w value indicates greater crop loss at a similar weed abundance. The closeness of the weed-crop relationship is reflected in both i_w significance and the overall model fit (R^2). The a_0 and i_w parameters were considered different among cropping systems if 95% confidence intervals did not overlap. Curve-fitting was performed in R version 3.2.0 (R Foundation for Statistical Computing, Vienna, Austria; R Development Core Team, 2015) using the `nls()` function. No random effects were included.

Competition models were compared pairwise between cropping systems using an overall F-test (Ryan et al. 2009):

$$F = \frac{(SSE_{Combined} - SSE_{Separate})/(df_{Combined} - df_{Separate})}{SSE_{Separate}/df_{Separate}} \qquad [2.2]$$

where $SSE_{Combined}$ is the sum of squares from the model where cropping systems were analyzed together; $SSE_{Separate}$ is the sum of squares from the model where cropping systems were analyzed separately; $df_{Combined}$ is the degrees of freedom from the model where cropping systems were analyzed together; and $df_{Separate}$ is the degrees of freedom from the model where cropping systems were analyzed separately.

Soil Indicators. Soil indicators were analyzed using mixed model ANOVA in R using `anova(lme())` within the nlme library, and setting `method="REML"`. Fixed effects were Year, System, and their interaction. Two random effects (Block, n=4; System-within-Block, n=16) were included in the model. Residuals were visually checked for homogeneity of variance. One outlier was removed from analysis of P. Zn was ln(x) transformed to correct heteroscedasticity; back-transformed least square means are reported. Least square means were grouped at significant (P<0.05) factor levels using the Tukey method using `cld(lsmeans())` within the lsmeans library.

Weed-Soybean Competition Index. Competition intensity between weeds and soybean under the Supplemented Seedbank treatment was quantified at the plot level in a "Competition Index". In Chapter 1, the Competition Index was used to evaluate weed-crop competition under the Standard Management treatment conditions. Here in Chapter 2, the Competition Index was calculated using data from the Supplemented Seedbank treatment in order to increase competition and to standardize weed community structure across cropping systems, thus nearly isolating the effects of soil properties on competition intensity.

In sampling, weed abundance was more closely linked with soybean biomass than soybean yield (temporally and spatially); therefore, the relationship between soybean biomass and weed abundance was less subject to chance variability. Thus, in this chapter we focus on analysis of the Competition Index with soybean biomass. Analyses of the Competition Index with soybean yield are included in Appendix A.

The Competition Index expresses soybean biomass loss per unit weed density (g stem^{-1}) or biomass (g g^{-1}), and a greater value indicates greater weed-crop competition intensity. The Competition Index was calculated using the following equation:

$$\text{Competition Index} = \frac{S_{wf} - S_{ss}}{W_{ss}} \quad [2.3]$$

where the numerator is soybean biomass in the Weed Free treatment minus that in Supplemented Seedbank (g m^{-2}), and the denominator is weed biomass (g m^{-2}) or density (stems m^{-2}) in the Supplemented Seedbank treatment. Because two weed metrics (density, biomass) were used, two Competition Index values were calculated in each plot.

Competition Indexes were analyzed using mixed model ANOVA in R. Software coding, fixed and random effects, assessment of residuals, and least square means comparisons were conducted the same way as for soil indicators. The Competition Index of Soybean Biomass vs Weed Biomass was cube-root-transformed before analysis to correct heteroscedasticity; back-transformed least square means are reported.

Relation of Weed-Soybean Competition to Soil Indicators. To assess the relationship of weed-free soybean production capacity and weed-crop competition intensity at the plot level with individual soil indicators, Pearson correlations were run between each of three competition responses (weed-free soybean biomass and two Competition Indexes) and each soil indicator. Pearson correlations were performed in R using `cor.test()`. Years were analyzed separately.

We used Partial Least Squares Regression (PLSR) to assess the relation between competition responses and all soil indicators simultaneously. PLSR is a multivariate technique in which components (aka "latent variables") are extracted from a set of predictor variables so as to maximize the explained variance on one or more response variables. PLSR behaves well in cases of relatively few observations and in cases of collinearity among predictor variables (Carrascal et al. 2009).

We constructed a separate PLSR model for each competition response in each year, for a total of six models, each with a single response variable. All soil indicators were included as predictor variables in each model. PLSR was performed in R using the `plsr()` function within the pls library, and setting `method="simpls"`. Because soil indicator units were incomparable, soil indicators were scaled (divided by their standard deviation) by setting `scale=TRUE`.

Standardized loadings (aka "weights", "component loadings", or "latent variable loadings") on the first component of each model are reported, along with the percent response variance explained by the first component. Standardized loadings express the contribution of each predictor variable to the meaning of the component (Carrascal et al. 2009). A larger standardized loading value (either + or -) indicates a greater influence of the predictor variable on the response variable, and the direction of the standardized loading (+ or -) on the first component expresses the direction of association between the predictor and response variable (Carrascal et al. 2009, Wortman et al. 2012). Within a component, the sum of squares of standardized loadings equals 1, and the square of each standardized loading equals the percent of the component's meaning that is retained in the predictor variable (Carrascal et al. 2009). Soil indicators retaining at least 5% of component information (square of standardized loading >0.05) were considered "influential".

Results and Discussion

Weed-Soybean Competition Modeling. The relationships between weed abundance and soybean performance differed among the four OCS cropping systems (Tables 2.1 and 2.2, Figures 2.1 and 2.2). However, results varied by soybean metric (biomass or yield), weed metric (biomass or density), and year.

First year. In 2014, the weed seeds that were added to the soil in the Supplemented Seedbank treatment germinated poorly, resulting in a limited range of weed abundances to use in modeling. Only two sub-plots in the RT system had greater than 200 g m^{-2} weed biomass, and all other sub-plots had less than 100 g m^{-2}. Weed densities were below 200 stems m^{-2} in all systems, and below 50 stems m^{-2} in HF (Figures 2.1 and 2.2).

Soybean biomass and yield responded differently to weeds in 2014. In soybean biomass, EWM was the only system that achieved significant (P<0.05) model fit, and it did so based on both weed biomass and density (Table 2.1). In contrast, soybean yield models in EWM fit the most poorly of any system. These results could suggest soybean yield was limited by some factor other than weeds in the EWM system, since soybean yields were low even at low weed abundance.

In the other three cropping systems in 2014, 3 out of 4 competition models fit significantly or marginally in HF, 1 out of 4 in LF, and 1 out of 4 in RT (Table 2.1). Although none of the HF models achieved a fit of P<0.05, HF was the most consistent system in showing competition between various soybean and weed measures (3 out of 4 HF models had $R^2 \geq 0.40$; Table 2.1).

Overall F-tests in 2014 showed that the competition models in EWM differed from all other systems, especially based on soybean yield (Table 2.2). The distinction of EWM was likely due to its lower weed-free soybean biomass and yield potential (inverse of a_0; Table 2.1). Other cropping systems did not differ in overall comparisons, with the exception that the model of soybean biomass vs. weed biomass differed between HF and RT (Table 2.2). In this case, weed-free soybean biomass potential and the competitive effect of weed biomass were lower in RT compared to HF.

Second year. In 2015, a different source of weed seeds was used in the Supplemented Seedbank treatment, which resulted in weed densities that were almost 10 times larger than the previous year (Figure 2.1 and 2.2). Weed biomass increased to a much smaller extent, illustrating the concept of constant final yield.

Due to a larger range of weed abundance in 2015, competition models for soybean yield were significant or marginally significant in most systems; however, only the RT system had a significant model for soybean biomass in 2015.

Although many of the models fit the data well and differed between cropping systems, none of the i_w parameters were significant, and differences between systems were driven by differences in soybean biomass and yield potential. Overall differences between competition models of EWM compared to other systems were mostly still present, but weaker in 2015 than 2014 (Table 2.2). Weed-free soybean biomass was greater in RT than both LF and EWM in 2015 (i.e., lower a_0; Table 2.1), which was reflected in overall F-tests (Table 2.2).

Table 2.1. Results of modified rectangular hyperbola competition modeling (Equation 2.1) between Soybean Yield and weed abundance in each cropping system (*HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage). Data from all three weed treatments (SM, WF, SS) were included in the models. Within a metric, parameter, and year, estimates followed by the same letter are not different based on 95% confidence intervals.

System	Soybean Biomass vs Weed Biomass					Soybean Biomass vs Weed Density				
	R^2	a_0 (plant g^{-1})		i_w (m^2 g^{-1})		R^2	a_0 (plant g^{-1})		i_w (m^2 stem^{-1})	
		estimate	P	estimate	P		estimate	P	estimate	P
2014										
HF	0.55	**0.0791 b**	<0.001	0.0070 a	0.066	0.09	0.0814 a	<0.001	0.0049 a	0.454
LF	0.00	**0.0965 ab**	<0.001	-0.0004 a	0.911	0.00	0.0958 a	<0.001	0.0000 a	0.974
EWM	0.47	**0.0988 a**	<0.001	**0.0075 a**	**0.045**	0.53	0.0957 a	<0.001	**0.0063 a**	**0.030**
RT	0.10	**0.0981 ab**	<0.001	0.0006 a	0.400	0.00	0.1019 a	<0.001	0.0000 a	0.992
2015										
HF	0.31	**0.1393 ab**	<0.001	0.0036 a	0.240	0.45	**0.1376 bc**	<0.001	0.0015 a	0.184
LF	0.22	**0.2083 a**	<0.001	0.0009 a	0.162	0.28	**0.2092 a**	<0.001	0.0002 a	0.113
EWM	0.44	**0.1873 a**	<0.001	0.0029 a	0.066	0.35	**0.1900 ab**	<0.001	0.0007 a	0.100
RT	0.76	**0.1114 b**	<0.001	**0.0072 a**	**0.023**	0.52	**0.1124 c**	<0.001	0.0020 a	0.168

System	Soybean Yield vs Weed Biomass					Soybean Yield vs Weed Density				
	R^2	a_0 (plant g^{-1})		i_w (m^2 g^{-1})		R^2	a_0 (plant g^{-1})		i_w (m^2 stem^{-1})	
		estimate	P	estimate	P		estimate	P	estimate	P
2014										
HF	0.40	**0.1480 b**	<0.001	0.0029 a	0.101	0.47	**0.1420 b**	<0.001	0.0064 a	0.052
LF	0.33	**0.1554 b**	<0.001	0.0048 a	0.094	0.01	**0.1630 b**	<0.001	0.0003 a	0.721
EWM	0.00	**0.1993 a**	<0.001	-0.0002 a	0.836	0.00	**0.1981 a**	<0.001	0.0001 a	0.884
RT	0.04	**0.1584 b**	<0.001	0.0003 a	0.543	0.44	**0.1440 b**	<0.001	**0.0025 a**	**0.035**
2015										
HF	0.82	0.2457 a	<0.001	**0.0068 a**	**0.014**	0.92	0.2472 a	<0.001	**0.0027 a**	**0.004**
LF	0.63	0.2683 a	<0.001	**0.0046 a**	**0.023**	0.83	0.2664 a	<0.001	**0.0012 a**	**0.004**
EWM	0.57	0.3136 a	<0.001	0.0050 a	0.056	0.51	0.3147 a	<0.001	0.0015 a	0.065
RT	0.49	0.2445 a	<0.001	0.0043 a	0.119	0.74	0.2298 a	<0.001	0.0020 a	0.055

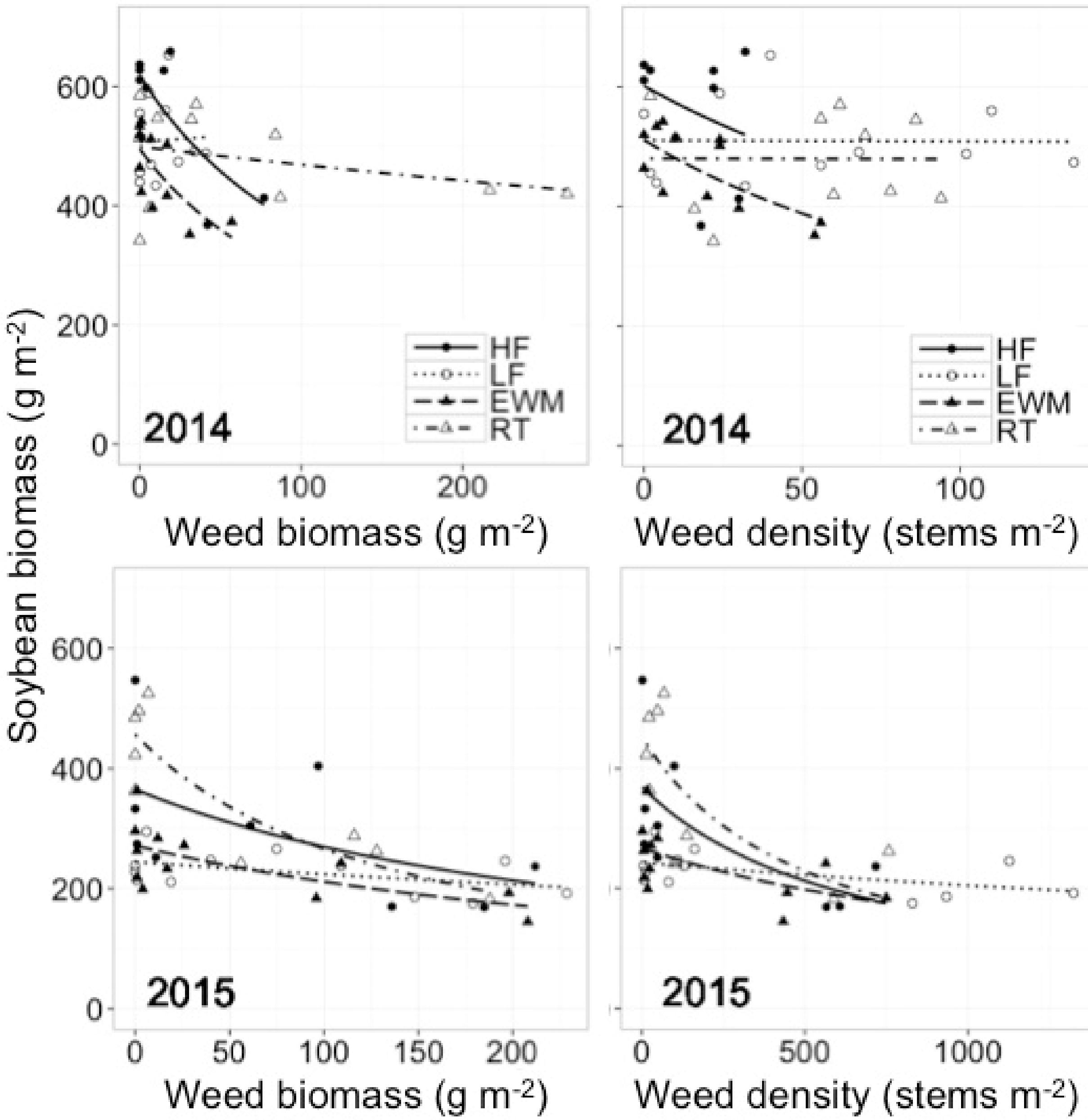

Figure 2.1. Relationships between soybean biomass and weed biomass (left) and between soybean biomass and weed density (right) in each year and cropping system (*HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage). Data from all three weed treatments (SM, WF, SS) were included in the models.

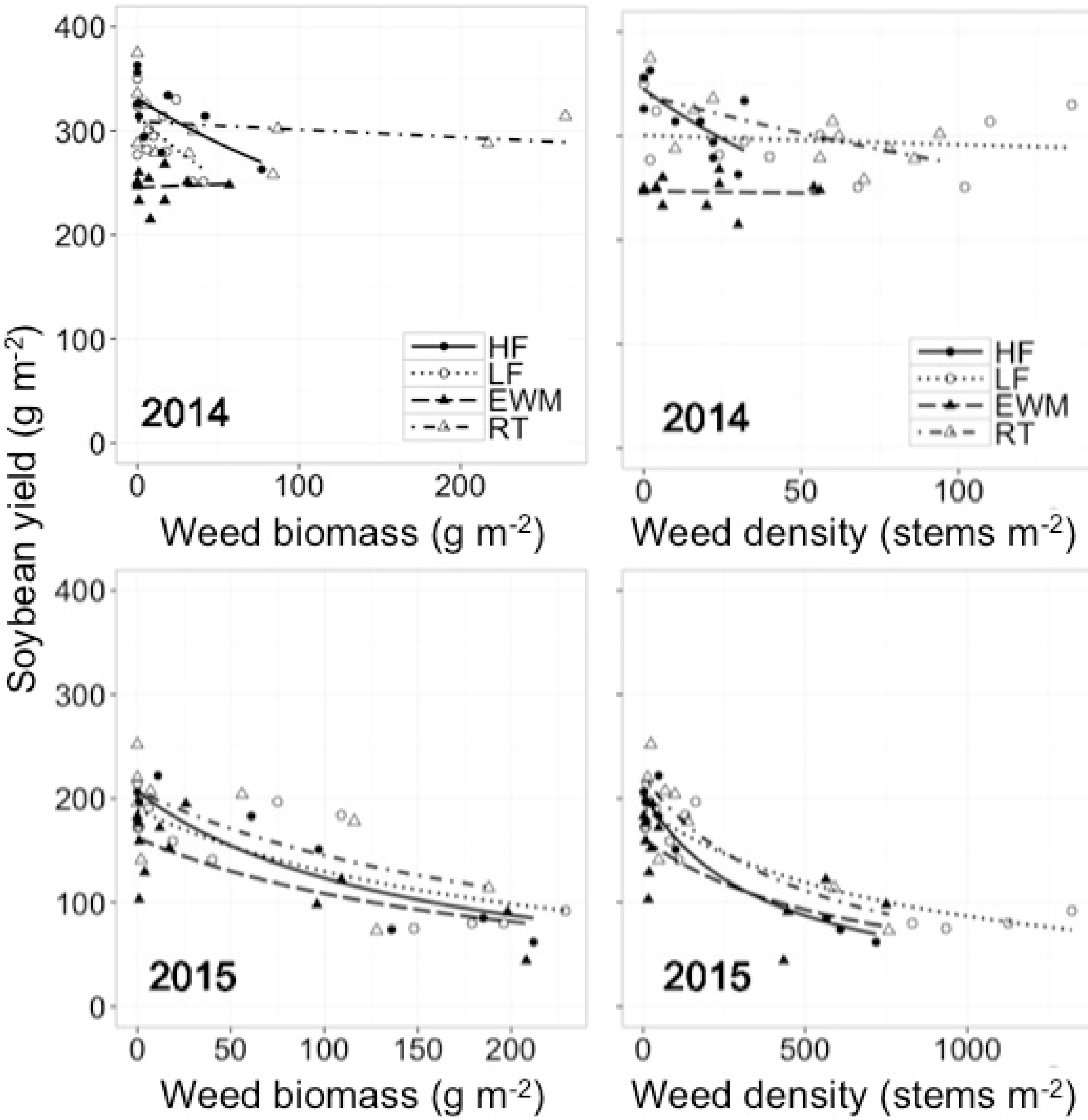

Figure 2.2. Relationships between soybean yield and weed biomass (left) and between soybean yield and weed density (right) in each year and cropping system (*HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage). Data from all three weed treatments (SM, WF, SS) were included in the models.

Table 2.2. Results of overall *F*-tests (Equation 2.2) comparing competition models between soybean performance and weed abundance in each cropping system (*HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage).

Year	Soybean Biomass vs Weed Biomass				Soybean Biomass vs Weed Density			
Comparison	*F*-value	ndf	ddf	*P*-value	*F*-value	ndf	ddf	*P*-value
2014								
HF vs LF	3.004	2	16	0.078	0.944	2	16	0.410
HF vs EWM	**8.223**	**2**	**16**	**0.003**	3.232	2	16	0.066
HF vs RT	**3.988**	**2**	**16**	**0.039**	1.240	2	16	0.316
LF vs EWM	3.379	2	18	0.057	**5.005**	**2**	**18**	**0.019**
LF vs RT	0.142	2	18	0.869	0.386	2	18	0.685
EWM vs RT	2.630	2	18	0.100	2.487	2	18	0.111
2015								
HF vs LF	3.427	2	17	0.056	**5.022**	**2**	**17**	**0.019**
HF vs EWM	2.451	2	17	0.116	2.852	2	17	0.086
HF vs RT	1.144	2	14	0.347	0.900	2	14	0.429
LF vs EWM	1.157	2	20	0.335	1.275	2	20	0.301
LF vs RT	**23.86**	**2**	**17**	**<0.001**	**12.85**	**2**	**17**	**0.000**
EWM vs RT	**16.63**	**2**	**17**	**<0.001**	**9.353**	**2**	**17**	**0.002**

Year	Soybean Yield vs Weed Biomass				Soybean Yield vs Weed Density			
Comparison	*F*-value	ndf	ddf	*P*-value	*F*-value	ndf	ddf	*P*-value
2014								
HF vs LF	1.753	2	16	0.205	2.262	2	16	0.136
HF vs EWM	**28.84**	**2**	**16**	**<0.001**	**29.20**	**2**	**16**	**<0.001**
HF vs RT	1.451	2	16	0.264	1.622	2	16	0.228
LF vs EWM	**16.37**	**2**	**18**	**<0.001**	**8.963**	**2**	**18**	**0.002**
LF vs RT	1.983	2	18	0.167	1.491	2	18	0.252
EWM vs RT	**12.80**	**2**	**18**	**<0.001**	**25.35**	**2**	**18**	**<0.001**
2015								
HF vs LF	0.447	2	17	0.647	2.731	2	17	0.094
HF vs EWM	2.954	2	17	0.079	3.012	2	17	0.076
HF vs RT	0.436	2	14	0.655	1.495	2	14	0.258
LF vs EWM	1.633	2	20	0.220	2.789	2	20	0.085
LF vs RT	0.495	2	17	0.618	1.424	2	17	0.268
EWM vs RT	3.292	2	17	0.062	**5.119**	**2**	**17**	**0.018**

Data from all three weed treatments (SM, WF, SS) were included in the models.

Soil Indicators. Many of the soil indicators measured in this research varied by year, cropping system, or their interaction (Table 2.3). Effects of year might indicate true differences between crop rotation entry points (since a different entry point was sampled each year), but might also be artificial effects due to unintentional handling differences, storage times, field spatial variability, or soil moisture at sampling.

Extractable nutrients. At the time of soil samplings in mid-June, total soil inorganic N was greater in 2014 than 2015 (Table 2.3), likely due to wet conditions in 2015 promoting leaching and denitrification. In 2014, soil inorganic N was greater in HF than LF and EWM, driven by differences in NO_3 concentration. In 2015, although there were no differences in total inorganic N, systems differed in terms of NO_3 and NH_4. The RT system had lower NO_3 than the EWM and the HF had greater NH_4 than the LF and EWM. Since weed species can vary in their ability to use different forms of mineral N (Di Tomaso 1995), such system differences might have impacted weed communities and weed-crop competitive interactions.

Extractable soil P (both years) and K (2015 only) were lower in LF and EWM systems, and greater in RT (Table 2.3). Low soil P and K in the LF and EWM systems was due to there being no P and K addition (LF) or only one composted poultry manure application (EWM) in these systems in the 9 yr prior to the nested experiment (besides a small amount of low analysis corn starter used in all systems). Other nutrients (Al, Ca, Fe, Mg, and Mn and Zn) did not vary among cropping systems.

Organic matter. Total soil C, N, and C:N ratio did not vary among systems in either year (Table 2.3). However, there was a significant year by system interaction because the RT had the lowest total C in 2014 and the greatest total C in 2015, possibly due to entry point effects, field spatial variability or sampling issues. The C and N composition of free and occluded particulate organic matter (fPOM and oPOM) differed between systems, especially in the second year of the experiment (Table 2.3). In 2015, the C:N ratio of fPOM was greater in EWM than HF and RT, indicating lower quality of organic matter that is less readily decomposable by soil microbes. Both oPOM-C and oPOM-N concentrations were lower in EWM than RT soils in 2015. Results were similar in 2014, although the patterns were not statistically significant (Table 2.3). These results suggest degradation of both fPOM quality and oPOM quantity under intense tillage and cultivation. These results might be interpreted as a reduction of soil resource pool size or diversity under EWM versus RT.

Table 2.3. Results from ANOVA on soil indicators. Within a row, lowercase letters indicate system differences within a year at P<0.05. Capital letters indicate system differences averaged across years at P<0.05. See text for abbreviations.

Indicator	Year	System	Y × S	2014				2015			
	P value			HF	LF	EWM	RT	HF	LF	EWM	RT
Extractable nutrients (mg kg^{-1})											
Inorganic N	**<0.001**	0.059	**0.024**	**13.9 a**	**10.2 b**	**10.8 b**	**11.9 ab**	7.3	6.1	7.6	6.1
NO_3-N	**<0.001**	0.155	**<0.001**	**11.7 a**	**7.2 b**	**7.8 b**	**9.3 ab**	**2.5 ab**	**2.9 ab**	**4.5 a**	**1.7 b**
NH_4-N	**<0.001**	0.450	**0.008**	2.2	3.0	3.0	2.6	**4.8 a**	**3.2 b**	**3.1 b**	**4.4 ab**
P	0.064	**0.010**	0.475	**11.5 AB**	**8.4 B**	**8.9 B**	**12.0 A**	**10.8 AB**	**8.0 B**	**8.7 B**	**12.0 A**
K	**<0.001**	**0.034**	**0.013**	94.0	91.0	93.2	101.5	**115.3 ab**	**94.6 b**	**103.5 b**	**128.8 a**
Al	0.471	0.499	0.720	1.2	1.3	1.5	1.4	1.2	1.3	1.5	1.3
Ca	0.610	0.567	0.456	3191	2900	3257	3319	3678	2643	3153	3672
Fe	0.072	0.578	0.201	0.44	0.56	0.69	0.55	0.64	0.57	0.66	0.71
Mg	**0.023**	0.273	0.465	343	351	330	342	349	378	335	364
Mn	**<0.001**	0.453	0.813	52.1	48.4	51.1	49.8	42.2	36.3	41.6	41.0
Zn	0.662	0.051	0.647	1.7	0.5	0.9	6.0	2.2	1.3	0.7	4.2
Organic matter											
Total soil C (g kg^{-1})	0.252	0.326	**0.025**	21.8	21.6	20.6	19.6	22.6	20.2	20.1	23.6
Total soil N (g kg^{-1})	0.551	0.504	0.413	1.95	1.91	1.75	1.77	1.91	1.89	1.69	2.04
Total soil C:N	0.839	0.808	0.384	11	11	12	12	12	11	12	12
fPOM C (g kg^{-1})	0.817	0.270	0.756	0.44	0.75	0.75	0.51	0.56	0.63	0.79	0.55
fPOM N (g kg^{-1})	0.908	0.615	0.211	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.03
fPOM C:N	0.539	0.062	**0.021**	24	25	27	25	**21 b**	**25 ab**	**34 a**	**22 b**
oPOM C (g kg^{-1})	**0.002**	0.117	**0.050**	1.63	1.68	1.38	1.46	**1.80 ab**	**1.90 ab**	**1.53 b**	**2.30 a**
oPOM N (g kg^{-1})	**<0.001**	0.241	0.078	0.11	0.12	0.10	0.10	**0.14 ab**	**0.15 ab**	**0.12 b**	**0.18 a**
oPOM C:N	**<0.001**	0.488	0.800	14	14	15	15	13	13	13	13
OM-LOI (%)	**0.046**	0.302	0.466	3.0	3.0	2.8	2.9	3.0	3.2	2.9	3.2
Active C (mg kg^{-1})	**0.040**	0.350	0.626	535	538	493	493	561	552	520	556
Respiration (g kg^{-1})	**0.013**	0.080	0.129	0.88	0.95	0.89	0.94	**0.86 ab**	**0.73 ab**	**0.70 b**	**0.94 a**
Nmin (µg g^{-1} $7d^{-1}$)	**0.005**	0.273	0.088	6.1	6.2	6.7	5.8	**11.3 a**	**9.2 ab**	**5.9 b**	**10.2 ab**
Structure											
Aggregate Stability (%)	0.294	0.016	0.449	**29 B**	**37 AB**	**32 B**	**40 A**	**24 B**	**30 AB**	**27 B**	**45 A**

Percent soil organic matter (OM-LOI) and active carbon were both greater in 2015 than 2014, although means separation did not show that OM-LOI differed between years (Table 2.3). Greater active carbon and OM-LOI in the second year might be due to differences in entry point, sampling conditions, or storage time (2014 samples were stored for 20 months, and 2015 samples for 8 months before analysis).

Soil respiration, measured as CO_2 evolution during a 4 d aerobic incubation, was lowest in EWM, highest in RT, and intermediate in HF and LF across years (Table 2.3). Greater respiration in RT than EWM indicates greater microbial activity in a system with historically less tillage, possibly related to accumulation of organic matter. Our results are in contrast to those of Vakali et al. (2011), who did not find differences in soil respiration among three long-term organic systems that varied in tillage intensity. The correspondence of respiration levels to oPOM-C and oPOM-N across systems is logical because soil organic matter is the food source of microbes. Microbial activity is related to resource uptake by plants. However, respiration does not give information about distinct microbial communities or their functions.

Potentially mineralizable N (Nmin), measured in a week-long anaerobic incubation, was lower in EWM than HF in 2015, but did not differ between cropping systems in 2014. Because Nmin was calculated as final minus initial NH_4^+ concentration in an incubation, variation in initial NH_4^+ concentration might have unduly affected Nmin estimates.

Structure. Aggregate stability was the most consistent soil health indicator across years, and was highest in RT, lowest in EWM and HF, and intermediate in LF. Aggregate stability is often closely linked with tillage and cultivation intensity (Moebius-Clune et al. 2016). Our results confirm those of Vakali et al. (2011), who found increased aggregate stability in an organic system with reduced tillage intensity. High aggregate stability protects soil structure against wind and water erosion and improves soil drainage. In a wet season such as 2015, soil with high aggregate stability might be expected to achieve better air exchange, resulting in more aerobic soil conditions, decreased denitrification, and increased oxygen availability to plant roots. In addition, stable aggregates provide physical protection for soil organic matter, allowing greater

Table 2.4. Results from ANOVA of Competition Indexes (Equation 2.3) in the Supplemented Seedbank treatment. The Competition Index between soybean biomass and weed biomass was cube-root-transformed before analysis; back-transformed least square means are reported. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage. 2014, Entry Point A; 2015, Entry Point B.

	Competition Index	
	Soybean Biomass vs WB[a]	Soybean Biomass vs WD[a]
	g stem^{-1}	g g^{-1}
2014		
HF	13.3721	3.7567
LF	0.0845	-0.8218
EWM	0.0004	0.2688
RT	-0.0331	-0.4676
2015		
HF	1.0102	0.2481
LF	0.2375	0.0434
EWM	0.4811	0.2029
RT	1.0348	0.2318
	P value	
Year	0.618	0.656
System	0.277	0.275
Year × System	0.334	0.303

[a] *WD* weed density, *WB* weed biomass

organic matter to accumulate in soil (Lehmann and Kleber 2015) that eventually becomes a slow-release source of nutrients (Marriott and Wander 2006).

Low ranking of the EWM system across multiple soil indicators (inorganic N, P, K, oPOM C and N, fPOM C:N, N mineralization, aggregate stability) suggests overall poorer soil quality under a system including intense tillage and low nutrient inputs. However, most effects were not consistently significant across years. Future performance of the EWM system could determine whether poor soil quality in EWM was a long-term effect, or a year-to-year effect influenced by specific tillage events during suboptimal soil moisture conditions.

Weed-Soybean Competition Index. At the plot level, the Competition Index between soybean biomass and weed biomass ranged from -11.92 to 87.27 g g^{-1}. The greatest value occurred in an HF plot where the Supplemented Seedbank treatment had only 1 g m^{-2} weed biomass, and all other values were less than 12 g g^{-1}. There were no significant effects in ANOVA analysis (Table 2.4). Cropping system least square means were wider ranging in 2014, reflecting unintentionally low weed abundance in the Supplemented Seedbank treatment due to poor weed seed germination. In 2015, when the Supplemented Seedbank treatment achieved consistently high weed abundance, the cropping system least square means of Competition Index between soybean biomass and weed biomass ranged from 0.23 to 1.03, and were numerically greater in HF and RT than LF and EWM.

Results from ANOVA of the Competition Index between soybean biomass and weed density were similar to those with the other metric, though with a narrower range (Table 2.4).

Relation of Weed-Soybean Competition to Soil Indicators

Correlations. Weed-free soybean biomass was not correlated with any soil indicators in 2014, but was positively correlated with several extractable nutrients (P, K, Ca), total soil C, and respiration in 2015 (Table 2.5). Correlation of weed-free soybean biomass with respiration suggests that soil microbial activity might have boosted soybean resilience to unfavorable weather conditions that reduced soybean biomass in 2015 compared to 2014.

Competition Indexes were positively correlated with several soil indicators in both years. Both Competition Indexes were correlated with Inorganic N and NO_3^- in 2014, and with K and Ca in 2015. Total soil C:N and respiration were also positively correlated with the Competition Index of soybean biomass vs. weed biomass in 2015.

It is noteworthy that three soil indicators (K, Ca, and respiration) were positively correlated with both weed-free soybean biomass and competition intensity. This could suggest that increasing K, Ca, and microbial activity stimulated soybean growth under weed free conditions, but also stimulated the competitive ability of weeds when weeds were present.

Table 2.5. Pearson correlations between soybean biomass growth responses and soil indicators. *P* values: .<0.1, *<0.05, **<0.01, ***<0.001

Soil Indicator	Weed Free Capacity		Competition Index vs Weed Density		Competition Index vs Weed Biomass	
	2014	2015	2014	2015	2014	2015
	R					
Extractable nutrients						
Inorganic N	0.29	0.03	**0.59** *	0.43	**0.65** *	0.13
NO_3-N	0.35	-0.14	**0.54** *	0.25	**0.61** *	-0.12
NH_4-N	-0.34	0.24	-0.09	0.13	-0.17	0.32
P	-0.06	**0.64** *	0.39	0.31	0.42	0.37
K	-0.07	**0.81** ***	0.32	**0.56** *	0.31	**0.74** **
Al	0.03	-0.24	-0.18	-0.13	-0.28	0.05
Ca	-0.07	**0.72** **	**0.53** .	**0.54** *	0.26	**0.71** **
Fe	-0.17	-0.00	-0.16	-0.15	-0.25	0.16
Mg	0.33	-0.18	-0.30	-0.30	-0.42	-0.36
Mn	0.43	0.05	**0.53** .	0.06	0.30	0.24
Zn	0.12	0.36	-0.08	0.11	-0.13	0.12
Organic matter						
Total soil C	-0.06	**0.66** *	0.40	0.42	0.33	0.41
Total soil N	-0.28	0.30	-0.01	0.09	0.13	-0.03
Total soil C:N	0.27	0.35	0.41	0.32	0.14	**0.57** *
fPOM C	-0.25	-0.17	-0.25	-0.26	-0.30	-0.23
fPOM N	-0.26	0.21	-0.35	0.02	-0.32	0.22
fPOM C:N	-0.18	-0.38	0.01	-0.21	-0.18	-0.41
oPOM C	0.09	0.34	0.33	0.01	**0.48** .	0.07
oPOM N	0.10	0.31	0.34	0.01	**0.50** .	0.02
oPOM C:N	-0.04	0.02	-0.13	0.05	-0.26	0.29
OM-LOI	-0.10	0.07	-0.39	-0.17	-0.15	-0.25
Active C	-0.11	0.15	-0.04	0.02	0.20	-0.11
Respiration	-0.06	**0.81** ***	-0.17	0.41	-0.27	**0.62** *
Nmin	-0.14	-0.17	-0.14	0.12	0.07	-0.11
Structure						
Aggregate Stability	-0.12	0.34	-0.10	-0.30	-0.11	0.14

Partial Least Squares Regression. The first component of each Partial Least Squares Regression model explained more than 50% of response variability and is focused on for reporting. Overall, the first components of the PLSR models identified most of the same influential soil indicators as did Pearson correlations. However, PLSR revealed a more complex story than correlation, showing a greater number of influential soil indicators in most cases.

In 2014, inorganic N, NO_3^-, and NH_4^+ had large loadings on the first component of the PLSR model for weed-free soybean biomass (Table 2.6), together retaining 48% of the information in the first component ($0.40^2+0.45^2+(-0.35)^2=0.48$). These results suggest that in

Table 2.6. Results of Partial Least Squares Regression with soybean biomass responses. Standardized loadings and response variance explained by the first component of each model are reported. Influential indicators are in bold; those retaining > 5% and <10% of component information are indicated by **.**, those retaining >10% *****, and those retaining >20% ******

Soil Indicator	Weed Free Capacity		Competition Index vs Weed Density		Competition Index vs Weed Biomass	
	2014	2015	2014	2015	2014	2015
Variance explained (%)	70.53	65.38	52.88	70.33	56.23	76.31
Extractable nutrients						
Inorganic N	**0.40 ***	-0.07	**0.30 .**	0.19	**0.33 ***	0.00
NO_3-N	**0.45 ****	-0.14	**0.26 .**	0.13	**0.31 .**	-0.11
NH_4-N	**-0.35 ***	0.12	0.00	0.03	-0.09	0.16
P	0.16	**0.31 .**	**0.23 .**	**0.31 .**	**0.27 .**	**0.23 .**
K	0.17	**0.30 .**	0.21	**0.42 ***	0.21	**0.44 ***
Al	0.00	-0.22	**-0.31 .**	-0.22	**-0.30 .**	0.00
Ca	0.02	0.18	**0.24 .**	**0.41 ***	0.17	**0.44 ***
Fe	-0.21	-0.06	**-0.27 .**	-0.11	**-0.28 .**	0.13
Mg	0.18	0.15	-0.03	-0.02	-0.10	-0.09
Mn	0.15	-0.03	0.16	0.02	0.10	**0.23 .**
Zn	0.15	**0.25 .**	-0.16	0.18	-0.14	0.12
Organic matter						
Total soil C	-0.05	**0.33 ***	**0.30 .**	**0.38 ***	**0.26 .**	**0.24 .**
Total soil N	-0.10	**0.26 .**	0.22	0.16	0.20	0.00
Total soil C:N	0.06	0.00	0.07	0.19	0.04	**0.34 ***
fPOM C	**-0.34 ***	-0.10	0.04	0.00	-0.04	0.12
fPOM N	**-0.31 .**	0.05	0.02	0.04	-0.05	0.20
fPOM C:N	**-0.32 ***	-0.14	0.05	0.00	-0.03	-0.11
oPOM C	0.00	**0.27 .**	**0.28 .**	0.11	**0.27 .**	0.07
oPOM N	0.00	**0.26 .**	**0.28 .**	0.11	**0.28 .**	0.04
oPOM C:N	0.05	-0.13	-0.16	-0.06	-0.19	0.15
OM-LOI	0.06	0.20	0.21	0.04	0.18	-0.09
Active C	-0.02	0.22	**0.29 .**	0.12	**0.29 .**	-0.03
Respiration	-0.07	**0.31 .**	-0.04	**0.34 ***	-0.11	**0.37 ***
Nmin	0.05	0.06	0.07	-0.17	0.04	-0.04
Structure						
Aggregate Stability	0.03	0.22	-0.03	0.14	-0.06	0.06

2014, greater soil inorganic N (especially NO_3^-) was associated with greater weed-free soybean biomass. Free/light POM C, N, and C:N had negative loadings on the first component, suggesting that greater fPOM C, N, and C:N values were associated with lower weed-free soybean biomass. It is notable that PLSR identified important drivers of weed-free soybean biomass in 2014, even when no individual soil indicators were correlated with weed-free soybean biomass (Table 2.5).

In 2015, soil drivers of weed-free soybean biomass appeared quite different. Soil indicators retaining at least 5% of information in the first PLSR component were (by decreasing importance): total soil C, respiration, P, K, oPOM C, oPOM N, total soil N, and Zn (Table 2.6). The importance of soil organic matter, respiration, and extractable nutrients in the second year echoes correlation results and might describe a complex set of drivers influencing soybean biomass production capacity under unfavorable weather conditions.

Soil indicator influences on Competition Indexes were mostly consistent between weed density and weed biomass metrics, but differed between years. Total soil C and P had positive loadings on the first component in both years. Additional indicators with positive loadings in 2014 were Inorganic N, NO_3^-, oPOM C and N, active carbon, and (in weed density only) Ca. Both Al and Fe had negative loadings in 2014. Additional indicators with positive loadings in 2015, echoing correlation results, were K, Ca, and Respiration. Total soil C:N and Mn were also influential in weed biomass only.

Based on the Resource Pool Diversity Hypothesis, we predicted less intense weed-crop competition with a history of greater soil organic matter and nutrient additions. However, in our data, competition intensity between weeds and soybean generally increased with increasing nutrient concentrations, echoing the results of weed-soybean competition modeling in the HF system. These results are in accordance with work showing greater weed-crop competition at higher soil nutrient levels (Di Tomaso 1995) and could be interpreted to contradict the RPDH.

It is interesting that Al and Fe were the only extractable nutrients with negative loadings for the Competition Indexes. Both of these nutrients tend to increase in solution concentration at lower pH (Brady and Weil 1999). Negative loadings of Al and Fe might suggest that competition intensity decreased with lower pH.

In 2015, increased respiration was positively correlated with competition. However, this might be due to soil respiration also being associated with a greater weed-free yield potential. Increased competition, therefore, might be caused by the soybean using a larger amount of resources at greater respiration levels.

It is important to note that previous studies testing the RPDH were conducted in long-term cropping systems that both included a wider spectrum of management practices (i.e. organic vs. conventional, rather than four different types of organic production) and that had a longer period of time to diverge (the Rodale Farming Systems Trial was initiated in 1981, and the OCS was initiated in 2005). We did not find support for our original hypothesis that weed-soybean competition would be negatively correlated with soil nutrients, organic matter, or structure. However, we demonstrated that even among different organic cropping systems, management history can affect chemical, biological, and physical soil health properties. A history of intense tillage under the EWM system reduced soil health, and should be interpreted as a caution to organic farmers against intensive tillage whenever possible. We also demonstrated that soil chemical (e.g. N, K, Ca, and Mn) and biological factors (e.g. respiration) were positively related to weed-soybean competition. More research is needed to disentangle the effect of soil properties on weed-crop competition and to determine the potential for interactions with crop type (e.g. corn vs. soybean).

EPILOGUE

Conclusions

In our experiment, organic cropping systems with differing management histories differed in weed communities, soil environment (extractable nutrients, organic matter, and structure) and soybean performance. Weed communities differed between cropping systems, and particular weeds were associated with particular cropping systems. Weed abundance and diversity were greater in the RT than EWM system. However, this did not translate into lower soybean yields. In fact, soybean yields were greater in RT than EWM. This apparent crop tolerance of weeds in the RT system mimics crop tolerance of weeds in other organic systems experiments (Ryan et al. 2009, 2010a), and is likely related to increased weed-free production capacity in RT due to greater soil health.

Non-linear regression showed that the relationship between soybean and weed abundance differed between cropping systems. The difference in the relationship was mainly due to differences in weed-free soybean biomass and yield production capacity. Soybean yield was lower in 2015 than in 2014, and in general soybean biomass and yield were greater in the HF and RT systems than the LF and EWM systems. However, results varied across metrics and years.

Soil indicators revealed multiple effects of cropping system management history, particularly in extractable soil nutrients, organic matter fractions, and soil health indicators. Soil differed between systems in N, P, and K, some organic matter fractions, and three of the five indicators of soil health. Although soybean biomass potential was not correlated with any of the soil metrics tested in 2014, soybean biomass potential was correlated with soil P, K, Ca, soil carbon, and respiration in 2015. Weed-crop competition was correlated with N, Ca, and Mn in 2014 and K, Ca, C:N, and respiration in 2015. Results show increased weed-soybean competition intensity from increased soil nutrient and respiration levels.

Overall, correlation and PLSR analyses showed that both weed-free soybean biomass and competition intensity increased with increasing soil nutrient concentrations, organic matter fractions, and soil health indicators. We found no evidence that increased soil health decreased weed-crop competition among the metrics tested in this research. This does not support our hypothesis or provide evidence for the RPDH. However, information from this research is still useful to farmers. Our results show an overall decline in soil health in the EWM system after 9-10 years of increased tillage regimen. This bolsters evidence that farmers need to be careful of wearing out their soil with excessive tillage, especially with low organic matter and nutrient inputs.

Suggestions for Future Research

As mentioned in the prologue, soybean's nitrogen fixing abilities mean that it differs from other crops in terms of nutrient use and requirements. Examining variability in soybean N fixation under the various cropping systems and weed abundances in this study will be informative in explaining some of the patterns we observed.

In our research, nonlinear modeling was a more informative approach than the Competition Index in describing weed-soybean competitive relationships in our experiment. As a metric, the Competition Index was highly sensitive to plot-scale variability, because its calculation compounded multiple sources of error instead of reducing them. In future weed-crop competition research, I suggest that replication, large sample size, and modeling be emphasized in field experiments, while sensitive metrics such as the Competition Index be reserved for experiments in more controlled conditions.

Perhaps interpretation of our PLSR results would be facilitated by condensing similar soil indicators into a smaller number of predictor variables. For example, several soil indicators were related to overall soil organic matter (OM-LOI, total soil C and N, oPOM C and N) and combining them into one or two predictors might increase the likelihood of seeing clear patterns in these predictors.

Personal Reflections

I began this Masters program excited about conducting research in agroecology, even if the ideas would not result in tangible improvements in the agricultural system possibly for decades. As the program went on, I became increasingly focused on how the results of my research would or would not translate into tangible improvements in the world outside the university. Now working in extension, I am even more motivated to listen closely to the issues farmers describe as most challenging – whether they can be helped by scientific research or not – and meet them where they are. I would now argue that the information created by agricultural research must be heard, understood, and applied by farmers in order to be of practical value. In order to be applied by farmers, it must reach them in a form they can understand and use. Moreover, the course of action suggested by research must be practical in the context of the complex economic, political, social, and personal undertaking that is a farm. I urge agricultural researchers to consider this as a primary metric for the success of their research. I propose these questions for anyone who finds them to consider.

(1) Is my research creating information of practical use to farmers?
(2) If so, what can I do to help farmers access the information?
(3) If not, why not?

Many research topics are fascinating and potentially very important but still not practically applicable in the lives of most farmers. Often this is the fault of economic, political, or social conditions that restrict farmers' decisions and actions. Such research must be accompanied by efforts toward economic, political or social change in order to have a real world impact. For this case I leave two follow-up questions:

(1) What economic, political, or social changes must happen before my research is of practical use?
(2) What can I do to help these changes happen?

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APPENDIX A
COMPETITION INDEX ANALYSIS WITH SOYBEAN YIELD

In this research, we used multiple metrics of weed abundance (density, biomass) and soybean performance (biomass, yield) to quantify weed-free soybean production capacity and weed-soybean competition intensity. Different metrics shed light on different aspects of weed-soybean competitive relationships (Tables 2.1 and 2.2; Figures 2.1 and 2.2). For example, in 2014, weed competition with soybean biomass was strongest (greatest R^2) in the EWM system, but weed competition with soybean yield was weakest (lowest R^2) in the EWM system.

Weed density, weed biomass, and soybean biomass were sampled in August of each year from two 0.25 m^2 quadrats in each sub-plot. Because soybean biomass was sampled in the same time and place as weed abundance, competition metrics using soybean biomass were the least subject to the least temporal and spatial variability. Thus, competition metrics using soybean biomass were used to relate competition intensity with soil indicators in Chapter 2.

In contrast, soybean yield was sampled in October from areas surrounding (but not including) the biomass quadrat areas. Because soybean yield was sampled after weed abundance in an adjacent area, competition metrics using soybean yield were more subject to temporal and spatial variability. However, competition metrics using soybean yield were still important to consider since they illustrated the impacts of weeds on soybean yield. In this appendix, Competition Indexes between soybean yield and weed abundance were calculated and related with soil indicators in the same manner as in Chapter 2.

Correlations with metrics based on soybean yield were fewer and weaker than those based on soybean biomass (Table 2.5), justifying our focus on soybean biomass in the main text. Weed-free soybean yield capacity was correlated with several soil nutrients and respiration (Table A.1). Competition Indexes were correlated with several soil nutrients and total soil C. However, results were inconsistent across years. Interestingly, inorganic N and NO_3 were negatively correlated with competition intensity based on soybean yield in 2015 (Table A.1), yet positively correlated with competition intensity based on soybean biomass in 2014 (Table 2.5). This shift might illustrate that factors influencing weed-soybean competition intensity depended on seasonal weather conditions.

Partial Least Squares Regression showed complex soil influences on weed-free soybean yield and competition intensity in both years (Table A.2). In the PLSR model of Competition Index of soybean yield vs. weed density in 2014, the second component is reported because it explained a greater percent of response variance (44.27%) than the first component (35.34%). The negative relation of inorganic N with competition intensity in 2015, which showed in correlation analysis, was not apparent in PLSR. Respiration was influential in both competition metrics (weed density and weed biomass), but was negatively related to competition intensity in 2014 and positively related in 2015 (Table A.2). This inconsistency further supports the idea that the drivers of weed-soybean competition intensity might vary with weather.

Table A.1. Pearson correlations between soybean yield growth responses and soil indicators. *P* values: .<0.1, *<0.05, **<0.01, ***<0.001

Soil Indicator	Weed Free Capacity		Competition Index vs Weed Density		Competition Index vs Weed Biomass	
	2014	2015	2014	2015	2014	2015
	R					
Extractable nutrients						
Inorganic N	0.29	**-0.49 .**	0.06	0.03	0.24	**-0.49 .**
NO_3-N	0.38	**-0.57 ***	0.17	-0.06	0.27	**-0.55 .**
NH_4-N	-0.42	0.27	-0.36	0.11	-0.22	0.23
P	**0.47 .**	0.25	0.02	**0.50 .**	0.10	0.23
K	0.28	0.43	-0.30	0.47	-0.06	0.41
Al	-0.19	-0.22	0.23	-0.08	0.20	0.33
Ca	0.02	0.25	-0.18	**0.49 .**	-0.03	0.40
Fe	-0.29	-0.02	-0.00	0.05	0.01	**0.54 .**
Mg	0.35	**0.47 .**	0.11	-0.06	0.03	-0.11
Mn	-0.09	-0.09	0.13	0.07	0.41	0.25
Zn	**0.54 ***	0.06	0.18	0.00	-0.11	-0.18
Organic matter						
Total soil C	-0.09	0.42	-0.46	**0.54 .**	-0.31	0.11
Total soil N	0.02	0.34	-0.24	0.21	-0.30	-0.18
Total soil C:N	-0.14	0.02	-0.19	0.24	0.05	0.44
fPOM C	-0.22	-0.01	-0.29	-0.13	-0.25	-0.00
fPOM N	-0.21	0.28	-0.30	-0.06	-0.26	0.20
fPOM C:N	-0.20	-0.25	-0.13	0.08	-0.13	-0.12
oPOM C	0.32	0.31	-0.17	-0.06	0.07	0.03
oPOM N	0.25	0.31	-0.21	-0.01	0.06	-0.06
oPOM C:N	0.22	-0.19	0.23	-0.09	-0.03	0.33
OM-LOI	0.16	0.33	-0.14	-0.02	-0.11	-0.17
Active C	-0.01	0.31	-0.03	0.09	0.17	-0.23
Respiration	0.27	**0.48 .**	-0.30	0.31	-0.42	0.35
Nmin	-0.19	0.33	-0.43	0.14	0.36	0.33
Structure						
Aggregate Stability	0.01	0.46	-0.02	0.06	-0.30	0.08

Table A.2. Results of Partial Least Squares Regression with soybean yield responses. Standardized loadings and response variance explained by the first component of each model are reported. Influential indicators are in bold; those retaining > 5% and <10% of component information are indicated by **.**, those retaining >10% *, and those retaining >20% **

Soil Indicator	Weed Free Capacity		Competition Index vs Weed Density		Competition Index vs Weed Biomass	
	2014	2015	2014	2015	2014	2015
Variance explained (%)	62.27	43.75	44.27	41.49	64.39	51.00
Extractable nutrients						
Inorganic N	**0.30 .**	-0.17	**0.37 ***	0.00	**0.26 .**	-0.14
NO_3-N	**0.34 ***	**-0.23 .**	**0.33 ***	-0.08	**0.32 ***	-0.22
NH_4-N	**-0.29 .**	0.13	-0.06	0.12	**-0.32 ***	0.14
P	**0.39 ***	**0.24 .**	0.22	**0.40 ***	0.09	0.19
K	**0.25 .**	0.20	0.04	**0.36 ***	0.08	**0.29 .**
Al	**-0.26 .**	-0.21	-0.20	-0.20	0.16	0.22
Ca	0.00	0.05	**0.23 .**	**0.30 ***	0.00	**0.28 .**
Fe	**-0.36 ***	-0.08	**-0.29 .**	-0.16	0.03	**0.28 .**
Mg	0.03	**0.23 .**	0.17	0.14	-0.14	-0.14
Mn	-0.03	-0.06	**0.34 ***	0.08	0.00	**0.28 .**
Zn	0.22	0.21	-0.12	0.10	-0.06	-0.02
Organic matter						
Total soil C	0.06	**0.27 .**	0.14	**0.41 ***	-0.17	0.00
Total soil N	0.14	**0.27 .**	0.14	0.20	**-0.24 .**	-0.21
Total soil C:N	-0.12	-0.10	-0.03	0.14	0.09	**0.33 ***
fPOM C	**-0.23 .**	-0.11	-0.07	0.04	**-0.32 ***	**0.23 .**
fPOM N	**-0.24 .**	0.06	-0.11	0.17	**-0.27 .**	**0.23 .**
fPOM C:N	-0.13	-0.19	0.05	-0.11	**-0.34 ***	-0.08
oPOM C	0.13	**0.28 .**	0.15	0.10	-0.02	-0.01
oPOM N	0.11	**0.27 .**	0.14	0.11	0.00	-0.08
oPOM C:N	0.07	-0.16	-0.02	-0.06	-0.08	**0.27 .**
OM-LOI	0.19	**0.26 .**	**0.29 .**	0.11	-0.16	-0.21
Active C	0.05	**0.25 .**	**0.33 ***	0.21	0.05	-0.18
Respiration	-0.03	**0.25 .**	-0.10	**0.33 ***	**-0.39 ***	**0.25 .**
Nmin	-0.10	0.14	0.15	0.00	**0.23 .**	0.03
Structure						
Aggregate Stability	0.06	0.23	-0.18	0.18	-0.22	-0.03

APPENDIX B

SOIL – COMPETITION ANALYSES COMBINING YEARS

The relation of soil indicators with weed-free soybean production capacity and weed-crop competition intensity differed between years, likely due to varying weather conditions (Figure 1.1). However, the same analyses conducted with data from both years combined also showed strong patterns. With data from both years combined, the results of Pearson correlations and PLSR were similar. Inorganic N, NO_3^-, and Mn were positively related to both weed-free soybean production capacity and competition intensity (Tables B.1 and B.2). Respiration and oPOM C:N were positively related to weed-free soybean production capacity (Table B.1), but not consistently related to competition intensity. The consistency of these results across two years that differed strongly in weather conditions is striking, and might indicate that inorganic N and respiration are primary drivers of weed-free soybean production capacity and competition intensity that were obscured by unfavorable weather when 2015 was analyzed alone.

Table B.1. Pearson correlations between soybean growth responses and soil indicators, with years combined. *WD* weed density, *WB* weed biomass. *P* values: .<0.1, *<0.05, **<0.01, ***<0.001

Soil Indicator	Weed Free Capacity		Competition Index (SS)			
			Soybean Biomass		Soybean Yield	
	Biomass	Yield	vs WD	vs WB	vs WD	vs WB
	R					
Extractable nutrients						
Inorganic N	**0.67 *** **	**0.74 *** **	**0.35 .**	**0.45 * **	**0.45 * **	**0.42 * **
NO_3^-	**0.66 *** **	**0.74 *** **	0.31	**0.42 * **	**0.49 ** **	**0.44 * **
NH_4^+	**-0.35 .**	**-0.45 * **	-0.08	-0.17	**-0.39 * **	-0.28
P	0.25	0.12	0.16	0.16	0.15	0.17
K	-0.03	-0.26	0.07	0.01	-0.31	-0.19
Al	-0.06	-0.06	-0.10	-0.15	0.11	0.12
Ca	0.24	0.03	0.29	0.12	-0.09	-0.02
Fe	-0.20	-0.24	-0.13	-0.20	-0.08	-0.05
Mg	-0.20	-0.03	-0.20	-0.29	-0.08	-0.09
Mn	**0.64 *** **	**0.60 *** **	0.32	0.28	**0.43 * **	**0.48 * **
Zn	0.22	0.31	-0.06	-0.09	0.26	-0.01
Organic matter						
Total soil C	0.22	0.01	0.22	0.16	-0.22	-0.17
Total soil N	0.07	0.08	-0.00	0.06	-0.05	-0.12
Total soil C:N	0.13	-0.14	0.21	0.06	-0.16	-0.03
fPOM C	-0.18	-0.08	-0.19	-0.21	-0.22	-0.19
fPOM N	-0.05	-0.01	-0.28	-0.25	-0.23	-0.20
fPOM C:N	-0.31	-0.20	-0.01	-0.10	-0.10	-0.10
oPOM C	-0.16	-0.25	0.11	0.13	**-0.33 .**	-0.14
oPOM N	-0.23	**-0.33 .**	0.08	0.08	**-0.39 * **	-0.20
oPOM C:N	**0.50 ** **	**0.59 *** **	0.00	0.02	**0.43 * **	0.26
OM-LOI	-0.20	-0.13	-0.20	-0.12	-0.12	-0.15
Active C	-0.18	-0.20	-0.05	0.06	-0.15	-0.02
Respiration	**0.68 *** **	**0.55 ** **	0.06	0.03	0.20	0.10
Nmin	**-0.44 * **	**-0.33 .**	-0.09	-0.07	-0.23	-0.06
Structure						
Aggregate Stability	0.24	0.26	-0.05	-0.02	-0.06	-0.04

Table B.2. Results of Partial Least Squares Regression with years analyzed together. Standardized loadings and response variance explained by the first component of each model are reported. Influential indicators are in bold; those retaining > 5% and <10% of component information are indicated by **.**, those retaining >10% *****, and those retaining >20% ******

Soil Indicator	Weed Free Capacity		Competition Index (SS)			
			Soybean Biomass		Soybean Yield	
	Biomass	Yield	vs WD	vs WB	vs WD	vs WB
Variance explained (%)	73.23	64.93	34.57	35.19	33.16	26.01
Extractable nutrients						
Inorganic N	**0.42 ***	**0.40 ***	**0.43 ***	**0.45 ****	**0.32 ***	**0.35 ***
NO_3^-	**0.42 ***	**0.41 ***	**0.42 ***	**0.45 ****	**0.34 ***	**0.37 ***
NH_4^+	**-0.26 .**	**-0.28 .**	-0.21	**-0.28 .**	**-0.27 .**	**-0.26 .**
P	0.06	-0.02	0.20	0.18	0.07	0.10
K	-0.10	-0.19	0.00	-0.08	-0.20	-0.17
Al	-0.06	-0.01	**-0.30 .**	**-0.26 .**	0.05	0.05
Ca	0.10	0.00	0.15	0.04	-0.06	-0.03
Fe	-0.18	-0.16	**-0.34 ***	**-0.34 ***	-0.03	-0.03
Mg	-0.12	-0.12	-0.06	-0.11	-0.16	-0.18
Mn	**0.36 ***	**0.33 ***	**0.29 .**	**0.26 .**	**0.24 .**	**0.29 .**
Zn	0.08	0.07	0.02	0.04	0.16	0.12
Organic matter						
Total soil C	0.04	-0.07	**0.26 .**	0.17	-0.15	-0.12
Total soil N	-0.01	-0.06	0.20	0.18	-0.10	-0.10
Total soil C:N	0.04	-0.01	-0.04	-0.11	-0.04	0.00
fPOM C	0.02	0.02	-0.05	-0.14	-0.10	-0.09
fPOM N	-0.02	-0.03	-0.08	-0.16	-0.17	-0.15
fPOM C:N	0.02	0.05	0.00	-0.04	0.07	0.05
oPOM C	-0.19	**-0.24 .**	0.00	-0.04	**-0.31 .**	**-0.29 .**
oPOM N	-0.22	**-0.27 .**	-0.03	-0.06	**-0.34 ***	**-0.32 ***
oPOM C:N	**0.31 ***	**0.32 ***	0.11	0.11	**0.31 .**	**0.30 .**
OM-LOI	-0.16	-0.18	0.03	0.02	-0.21	**-0.23 .**
Active C	-0.15	-0.19	0.10	0.07	**-0.25 .**	**-0.23 .**
Respiration	**0.25 .**	0.15	**0.23 .**	0.17	0.08	0.10
Nmin	**-0.28 .**	**-0.27 .**	-0.19	-0.20	**-0.24 .**	**-0.23 .**
Structure						
Aggregate Stability	0.06	0.02	0.11	0.08	0.00	-0.02

APPENDIX C

NUTRIENT ADDITION TREATMENTS

Two nutrient treatments (Nitrogen Added and Phosphorous Added) were implemented to evaluate soybean and weed response to N and P availability. Nitrogen Added sub-plots received 50 kg N ha^{-1} as Chilean nitrate (16-0-0 N-P_2O_5-K_2O, North Country Organics, Bradford, VT, USA). Phosphorous Added sub-plots received 50 kg P_2O_5 ha^{-1} as triple super-phosphate (0-48-0 N-P_2O_5-K_2O, The Espoma Company, Millville, NJ, USA). Fertilizers were broadcast on the soil surface immediately after soybean planting. Triple super-phosphate was used despite violating organic standards because a single-nutrient, quick-release, organically approved P source was not available. Nutrient addition treatments were not implemented in EWM in 2014 due to space limitations[2].

Mixed model ANOVA was used to analyze soybean biomass, soybean yield, total weed density and biomass in the nutrient treatments (Nitrogen Added, Phosphorous Added, Standard Management). Because Nitrogen Added and Phosphorous Added were not implemented in the EWM system in 2014, nutrient treatment data were analyzed separately in the two years. Fixed effects were System, Treatment, and their interaction. Two random effects (Block, n=4; System-within-Block, n=16) were included and each was estimated as mean and variance of a normal population. Residuals were visually checked for homogeneity of variance. Weed density and weed biomass data were ln(x+1) transformed to correct heteroscedasticity; back-transformed least square means are reported. Least square means were grouped at significant (P<0.05) factor levels using the Tukey method.

There was no measurable response of weed or crop growth to N or P addition in any cropping system or year (Table C.1). Lack of response to phosphorous was surprising, considering that soil extractable P in LF and EWM was lower than in RT (Table 2.3). The LF

[2] A separate nested experiment co-occurred in EWM, entry point A.

Table C.1. Results from ANOVA of weed biomass and weed density in the three nutrient treatments (*N* Nitrogen Added, *P* Phosphorous Added, *SM* Standard Management) in two years. Years were analyzed separately. Fixed effects are reported. Random effects were Block and System-within-Block. Weed biomass and weed density data were ln(x+1) transformed to correct heteroscedasticity; back-transformed least square means are reported. Means followed by the same letter are not different at P<0.05. Lowercase letters indicate system differences within a year, averaged across treatments. *HF* High Fertility, *LF* Low Fertility, *EWM* Enhanced Weed Management, *RT* Reduced Tillage.

System	Soybean Biomass			Soybean Yield			Weed Biomass			Weed Density		
Factor	N	P	SM	N	P	SM	N	P	SM	N	P	SM
2014[a]	(g m^{-2})			(g m^{-2})			(g m^{-2})			(stems m^{-2})		
HF	461	410	490	313	288	302	29	31	38	**18 b**	**18 b**	**25 b**
LF	508	512	527	247	287	287	27	23	13	**63 a**	**49 a**	**56 a**
RT	446	525	475	294	282	288	142	30	69	**55 a**	**46 a**	**69 a**
	P value											
System	0.407			0.304			0.051			**0.017**		
Treatment	0.622			0.824			0.454			0.561		
Interaction	0.510			0.463			0.505			0.944		
	Soybean biomass			Soybean yield			Weed Biomass			Weed Density		
	N	P	SM	N	P	SM	N	P	SM	N	P	SM
2015	(g m^{-2})			(g m^{-2})			(g m^{-2})			(stems m^{-2})		
HF	301	321	332	152	156	185	71	59	41	**50 a**	**55 a**	**63 a**
LF	225	273	241	104	168	170	42	63	50	**98 a**	**116 a**	**117 a**
EWM	263	311	247	167	184	162	20	24	12	**22 b**	**18 b**	**28 b**
RT	339	354	388	153	168	183	42	59	19	**96 a**	**77 a**	**82 a**
	P value											
System	0.104			0.776			0.063			**<0.001**		
Treatment	0.439			0.094			0.243			0.482		
Interaction	0.899			0.435			0.953			0.760		

[a] Nutrient addition treatments were not implemented in EWM in 2014.

system had no P additions for 9 yr prior to the nested experiment (besides a small amount of low analysis corn starter used in all systems) and long-term nutrient depletion has been expected (B Caldwell, C Mohler, personal communication).